Chasing the Unicorn: RHIC and the QGP

Unicorn = fantastic and mythical beast!

RHIC = Relativistic Heavy Ion Collider @ Brookhaven Natl. Lab (BNL):
collide large nuclei at high energies (also: SPS & LHC @ CERN)

QGP = Quark Gluon Plasma =
New *state* of hadronic matter, in
thermodynamic *equilibrium* at temperature $T \neq 0$

Q: Has RHIC made the QGP?

1. QCD @ nonzero temperature: what is the QGP?

2. The QGP on the Lattice: numerical "experiment"

3. "Gluon Stuff" @ RHIC:
   the (high-pt) tail wags the (low-pt) body of the Unicorn

A: *Some* new *kind* of matter has been created

QCD at nonzero temperature: restoration of chiral symmetry

Like a magnet: *broken* at low temperature,
restored at some finite temperature.

up & down quarks: "flavor" symmetry = $SU_L(2) \times SU_R(2) = O(4)$

with strange: $SU_L(3) \times SU_R(3)$

In broken phase, (approx.) "spin waves"
= (almost massless) pions, K's, η

(What about η' from extra axial U(1)? Instantons....
Could dramatically affect transition properties with *light* quarks.)

Deconfinement as a *Global* Z(3) Symmetry

Multiply each quark by a constant phase:

$$q \longrightarrow e^{2\pi i/3} q \quad , \quad \overline{q} \longrightarrow e^{-2\pi i/3} \overline{q}$$

Mesons and baryons don't change:

$$\overline{q}q \longrightarrow \overline{q}q \quad , \quad qqq \longrightarrow (e^{2\pi i/3})^3 qqq = qqq$$

but q, qq, etc, do not. Could use exp(- 2 π i/3), too = Z(3) symmetry.

Z(3) spin = *Polyakov loop*
= *propagator* "test" quark =>

$$\ell = \frac{1}{3}\, \mathrm{tr}\, \mathcal{P} \exp \left(ig \int_0^{1/T} A_0 \, d\tau \right)$$

= (trace) color Aharonov-Bohm phase.

g = QCD coupling constant. For small g, loop ~ 1.

Only valid in a pure gauge theory, without dynamical quarks.
In QCD, is the Z(3) symmetry approximate?

Deconfinement & Polyakov Loops

't Hooft: part of *local* SU(3) is *global* Z(3) $\qquad \ell \to e^{2\pi i/3}\ell$

At T=0, confinement => *quarks don't propagate* => *UN*broken Z(3) symmetry

$$\langle \ell \rangle = 0 \ , \ \ T < T_{deconf}$$

As T→∞, by *asymptotic freedom*, g^2 small, pert. thy. ok, => loop is near one (times Z(3) phase).
=> deconfined phase in which quarks *propagate*:

$$\langle \ell \rangle \neq 0 \ , \ \ T > T_{deconf}$$

Deconfinment *opposite* to spins:

Z(3) broken at *high*, and not *low*, temp.

Order of Phase Transitions

Relation between deconfining and chiral transitions? 1 or 2 trans.'s?

For QCD, *both* Z(3) and chiral symmetries are *approximate*.

Strongly First Order Transition(s)?

"Of course"! Hadrons ≠ Quarks & Gluons.

Limits:

Deconfining transition (NO quarks): cubic invariant is Z(3) symmetric: ℓ^3

first order deconfining trans. (Svetitsky & Yaffe).

colors => ∞: first order deconf.'g trans.

Chiral transition: two massless flavors: O(4) sym. => *second order chiral trans.*

three massless flavors: *cubic* invariant $\det(\Phi)$ => *first order chiral trans.*

if axial U(1) restored: *first order chiral transition* for 2 & 3 flavors

(RDP & Wilczek)

The “Unicorn”:

Quark-Gluon Plasma =

Deconfined,
Chirally Symmetric “Phase”
at nonzero temperature

But how to compute
properties of the QGP?

QGP on the Lattice

Lattice: compute from *first* principles as lattice spacing a=>0. 2004:

Only gluons (no qks, pure gauge): present methods close to a=0!

T_d ~ 270 ± 10 MeV
Weakly first order deconfining trans. (Some masses ↓ by ~10).

Non-perturbative QGP from T_d => 3 T_d. *No* "of course"

QCD: present methods *not* close to a=0. *All* results tentative.

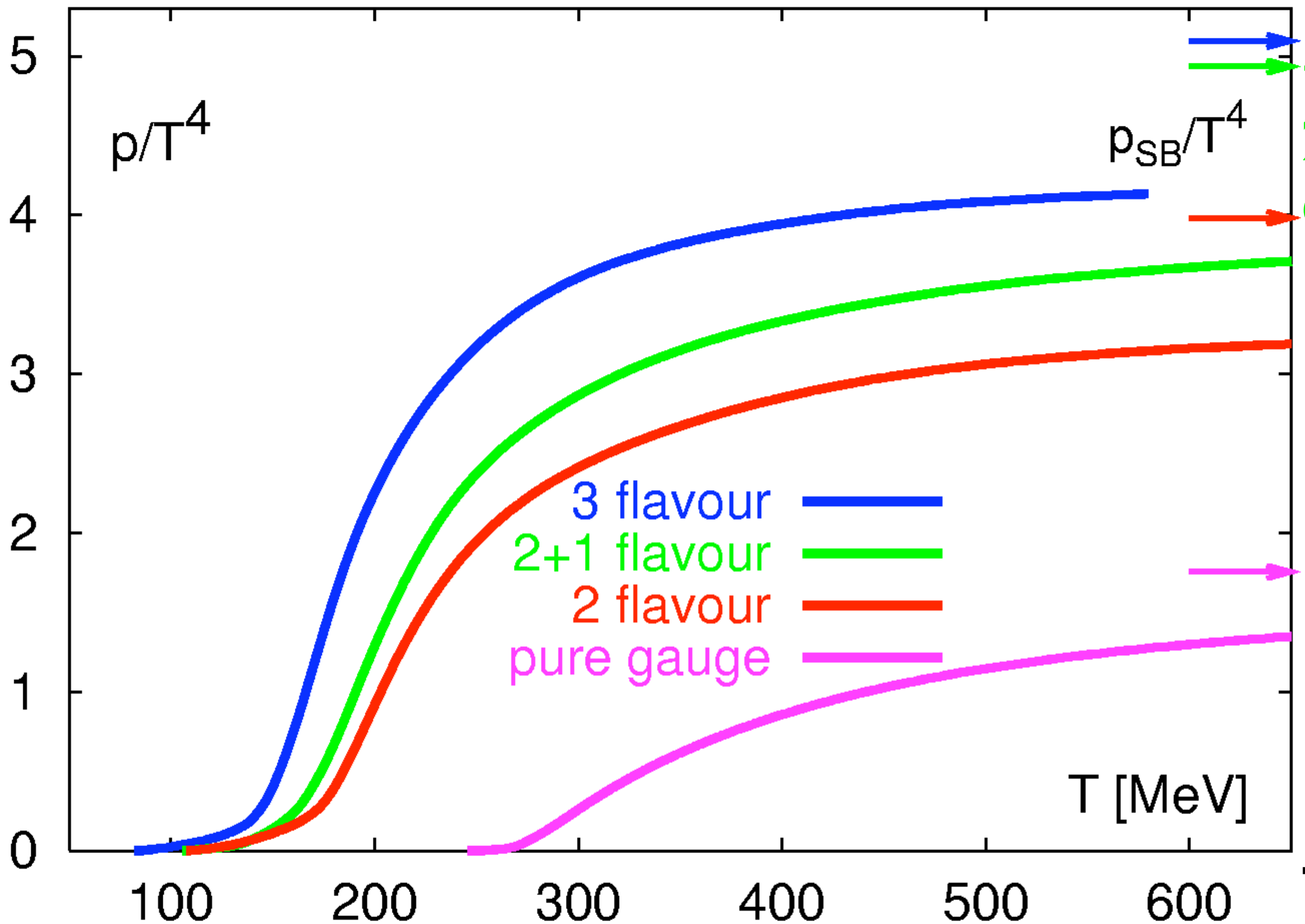
T_c ~ 175 ± ? MeV
Only *one* transition (chiral = deconfining)

Order? '04: crossover.
"Flavor independence": pressure *with* qks ~ with*out* qks.

Lattice: pressure vs temp., pure glue to QCD

p(T)=pressure. Asymptotic freedom => p/T^4 = const. as T $\rightarrow \infty$

p/T^4↑



<=ideal gas: 2+1 flavors = QCD

<=ideal gas: pure glue

T=>

Pure glue: ↑Tc ~ 270. 1st order phase transition

2+1 fl's = QCD: ↑Tc ~ 175. No phase transition: "crossover"

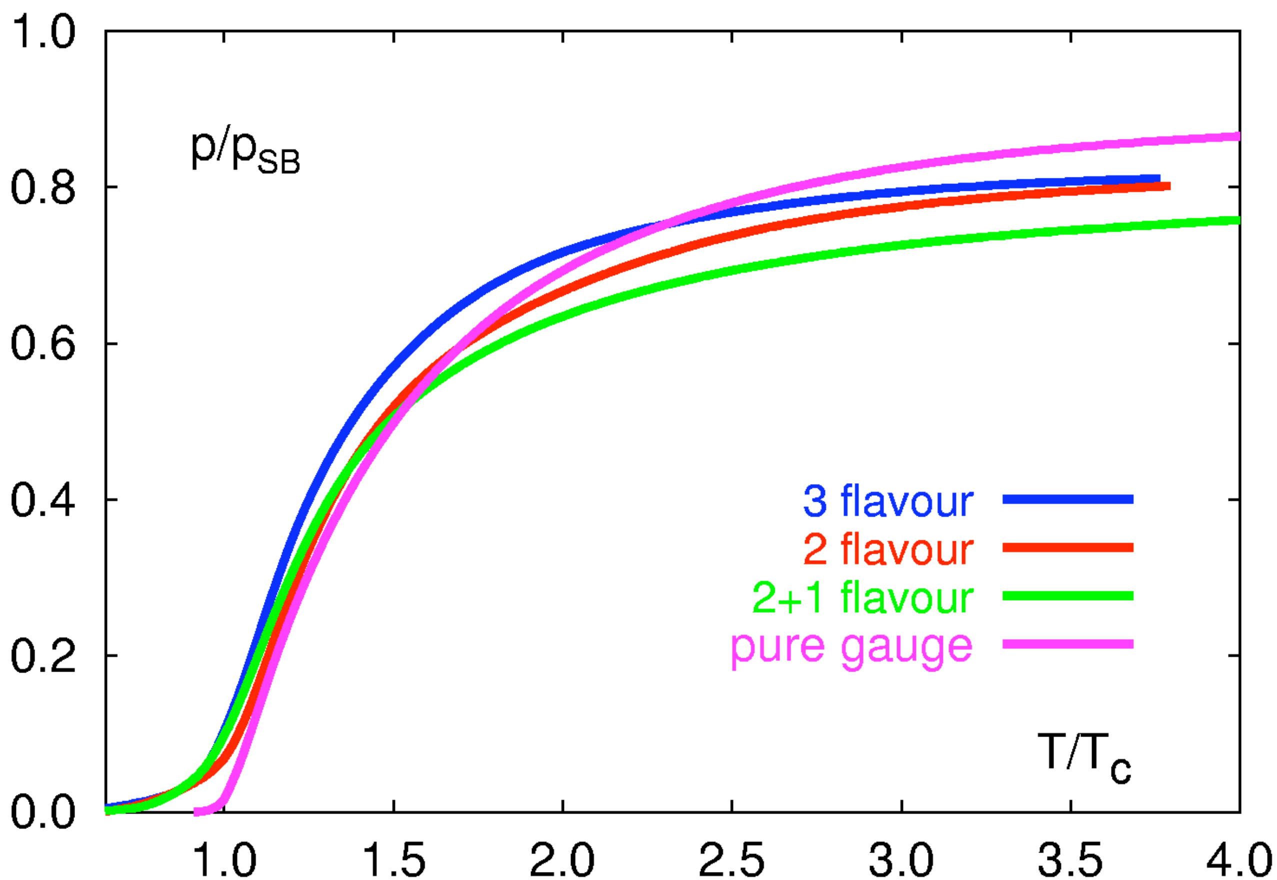
Lattice: "Flavor Independence"

Lattice finds *amazing* property: properly scaled, pressure *with* quarks like that *without*: *Bielefeld.*

$$\frac{p}{p_{ideal}}\left(\frac{T}{T_c}\right) \approx universal$$

1.0=>

pressure/ ideal gas↑



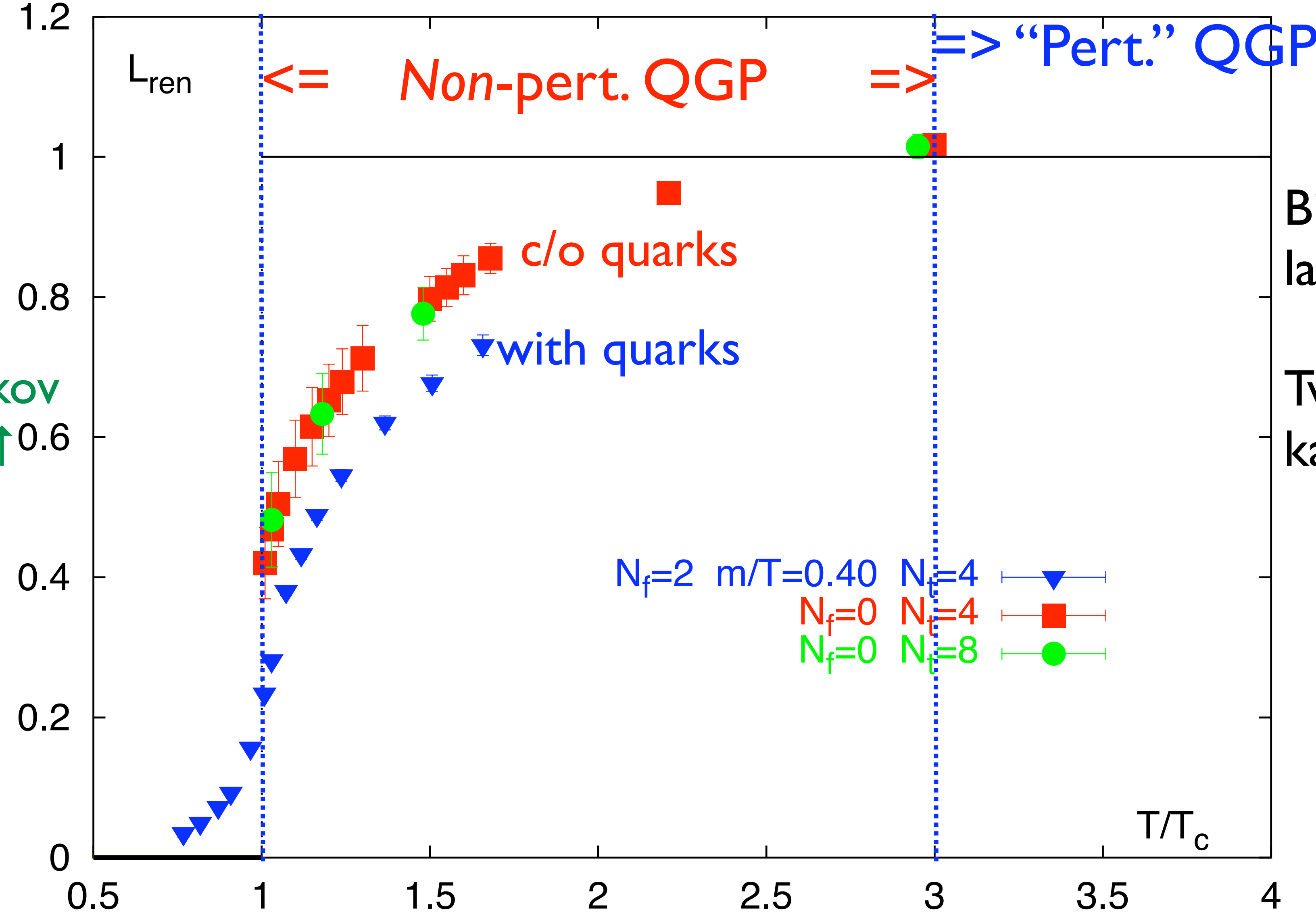
T/Tc=>

=> pressure *dominated by gluons?*

Non-pert. QGP for Tc => ~ 3 Tc

Ren.'d Polyakov loop with qks ~ as pure gauge => dominated by gluons?

Pert. thy: loop near one. Loop far from one: *non-pert. regime.*



Ren'd Polyakov loop ↑

Tc

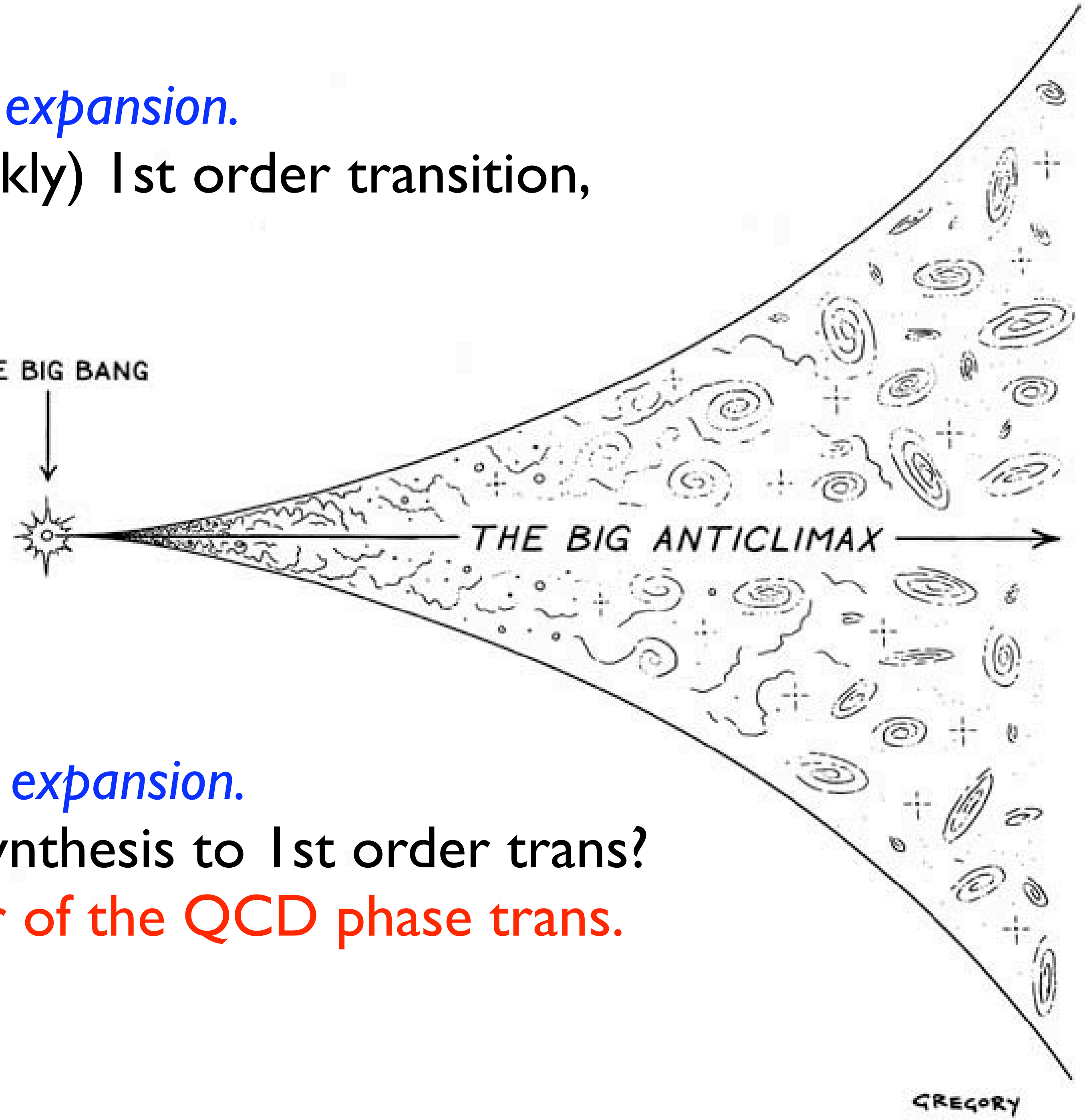
T/Tc=>

Bielefeld: lat/0312015

Two flavors, kaon masses

Early universe @ ~μsec: QCD phase transition

In AA collisions, *rapid expansion.*
Not sensitive to (weakly) 1st order transition,
indicated by lattice.



In early universe, *slow expansion.*
Sensitivity of nucleosynthesis to 1st order trans?
Goal for lattice: order of the QCD phase trans.
'04: crossover. '08?

The QGP Exists!
Hunting for the "Unicorn" in Heavy Ion Collisions

"Unicorn" & the QGP: Scott, Stock, Gyulassy...

Hunters = experimentalists, "all theorists are dogs..."

Why do AA? Big transverse size.

One can collide:

pp: protons on protons. Benchmark for "ordinary" strong int.'s

AA: nucleus with atomic number A on same.

dA: deuteron (N+P) on nucleus. Serves as another check.

Why AA? Baryons are like hard spheres, so nuclear size $\sim A^{1/3}$

Biggest: Pb (lead) or Au (gold), A ~ 200 => r_A ~ 7.

Transverse radius of nucleus $\sim A^{2/3}$ => trans. size ~ 50 x proton.

A ~ 200 close to A $\rightarrow \infty$ = *infinite* nuclear matter?

AA collisions at high energy: where?

Basic invariant: total energy in the center of mass, $E_{c.m.} \equiv \sqrt{s}$

For AA collisions, energy *per* nucleon is $\sqrt{s}/A \equiv \sqrt{s_{NN}}$

Machines	$\sqrt{s}/A$	
SPS @ CERN	5 => 17 GeV	fixed target
**** RHIC @ BNL	20, 130, 200 GeV	collider, > 2000
LHC @ CERN	5500 GeV = 5.5 TeV	collider, > 2007
SIS200 @ GSI	2 => 6 GeV	fixed target, > 2010

SPS = Super Proton Synchotron: CERN @ Geneva, Switzerland.
RHIC = Relativistic Heavy Ion Collider: BNL @ Long Island, NY.
LHC = Large Hadron Collider.
SIS = SchwerIonenSynchrotron: GSI @ Darmstadt, Germany.

Essentials of AA collisions

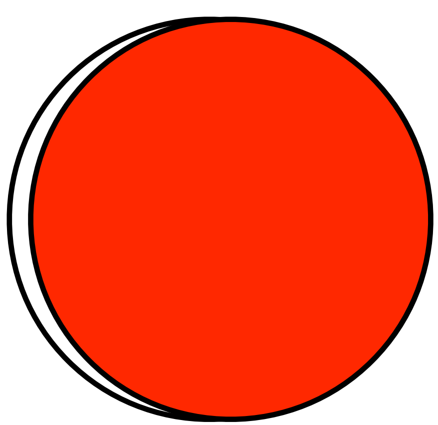
At energies >> mass, nuclei *slam* through each other.

Particles very different *along* beam direction, vs. *transverse* to beam.

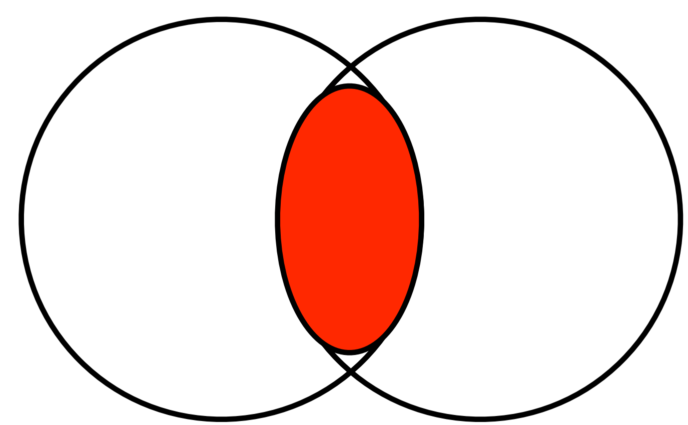
In collider: *ignore* along beam; look *just* perpendicular to beam
”central” or zero rapidity (rapidity ~ velocity along beam.)
90° to beam => few baryons => most likely to see nonzero temp.

Consider distribution of particles *only* in transverse momentum, p_t
Most particles at p_t = 0, fall off with increasing p_t. Thermal?

Central:
Maximum
Overlap



Peripheral=>
“Almond” of
overlap region



Typical Heavy Ion Event @ RHIC

Experiments @ RHIC:

"Big" expts: ~ 400 people
STAR & PHENIX

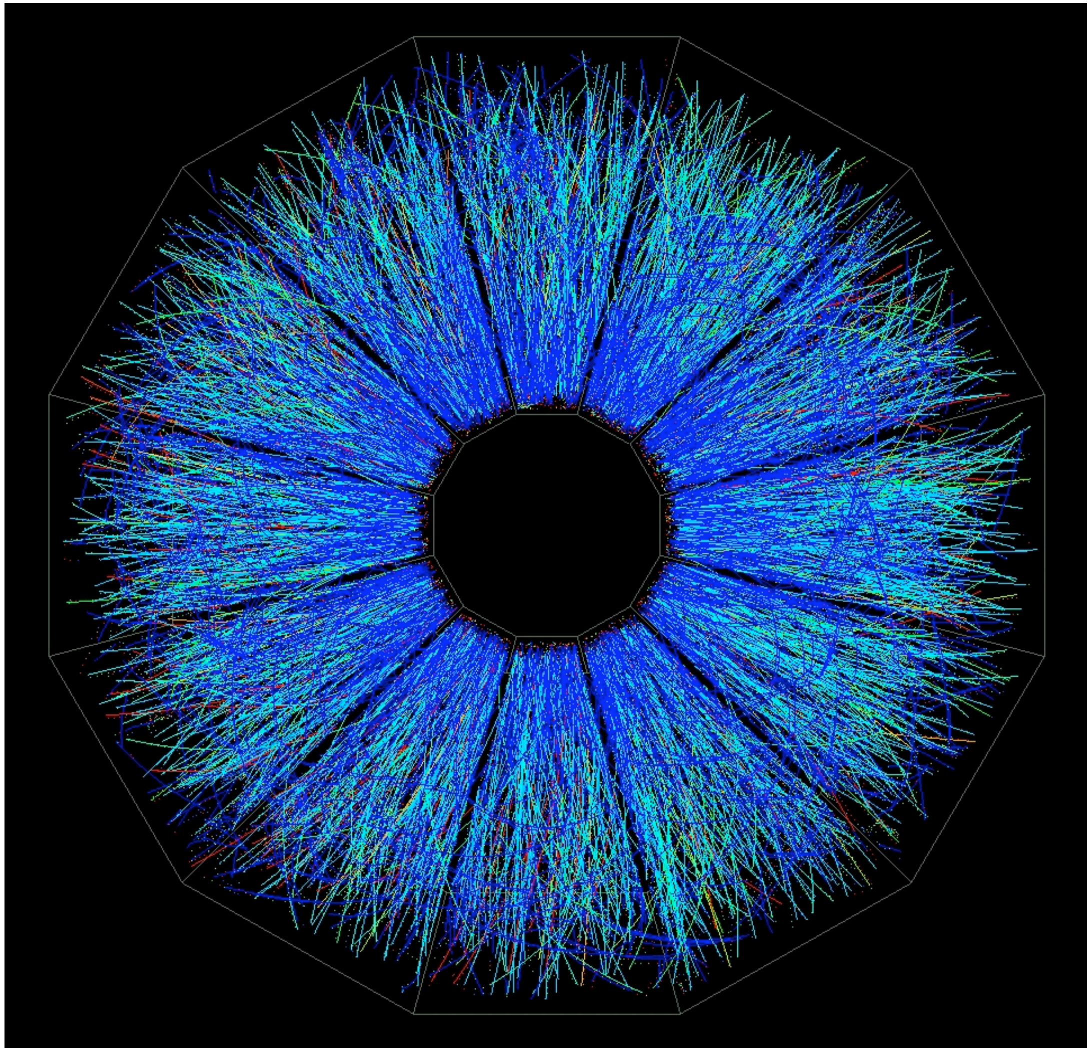
"Small" expts.: ~ 50 people
PHOBOS & BRAHMS

Note: total # particles ~
total # experimentalists
~ log(total energy)

theorists
~ log(log(total energy)).

Need hunters more than dogs...

Total # particles(/unit rapidity)
~ 900↓

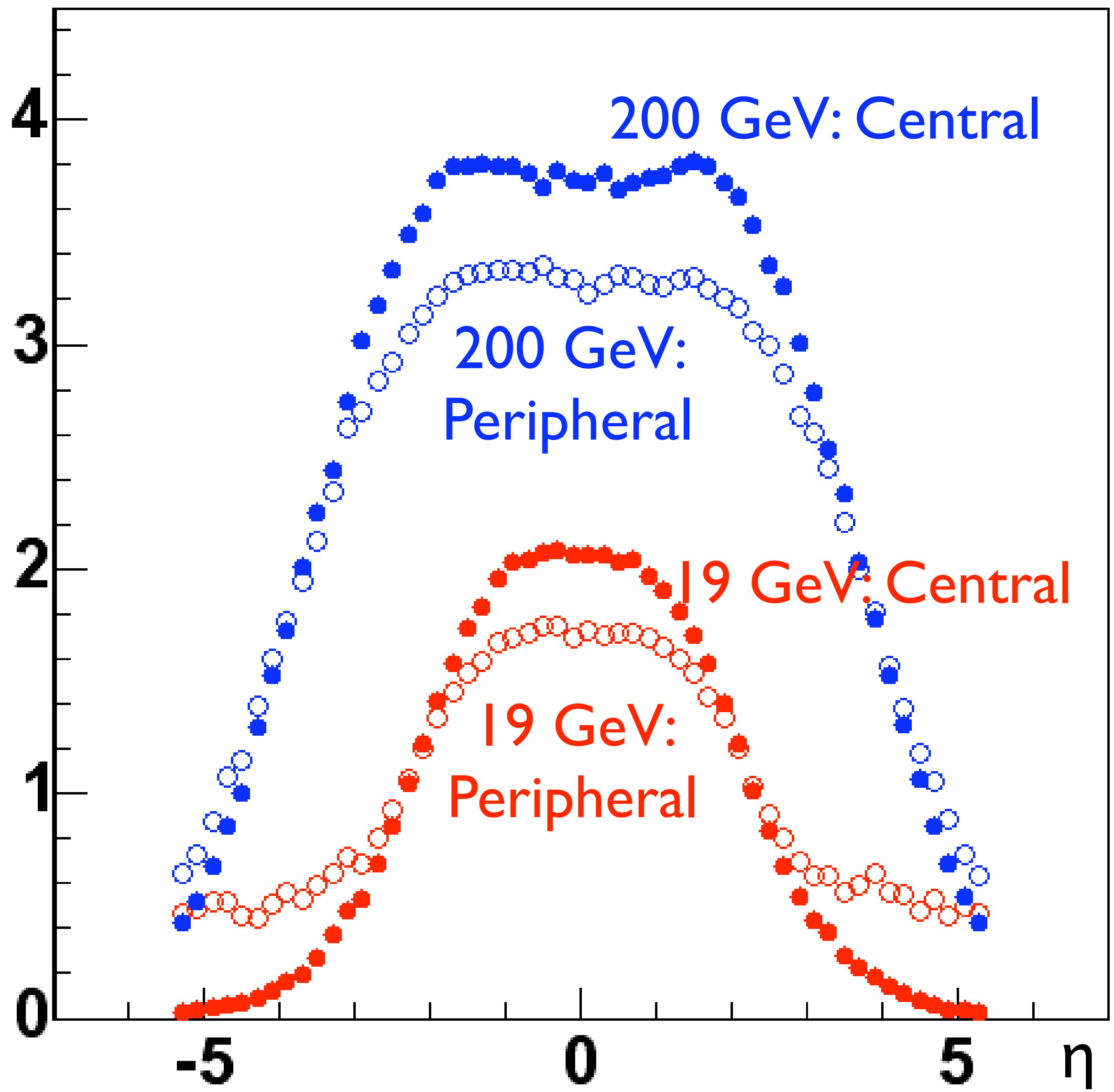


Particle Distributions vs η, Energy: "Central Plateau" @ RHIC

dN/dη / # participants

N = # particles

Particle dist.'s *qualitatively* same between central & peripheral.



η = pseudo-rapidity

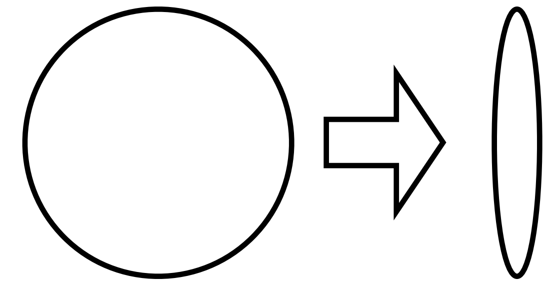
200 GeV = Highest energy @ RHIC
900 particles/unit η

19 GeV = Highest energy @ SPS
600 particles/unit η

No big changes in overall multiplicity

Why do AA? "Saturation" as a Lorentz Boost

At high energies, incident nucleus is *Lorentz contracted.*
=> color charge of incident nucleus gets "squashed".



$\leftarrow A^{1/3} \rightarrow$

McLerran & Venugopalan: color charge bigger by $A^{1/3}$

$A \rightarrow \infty$: can use *semi-classical* methods.

@ central rapidity, gluon *saturation* = Color Glass.

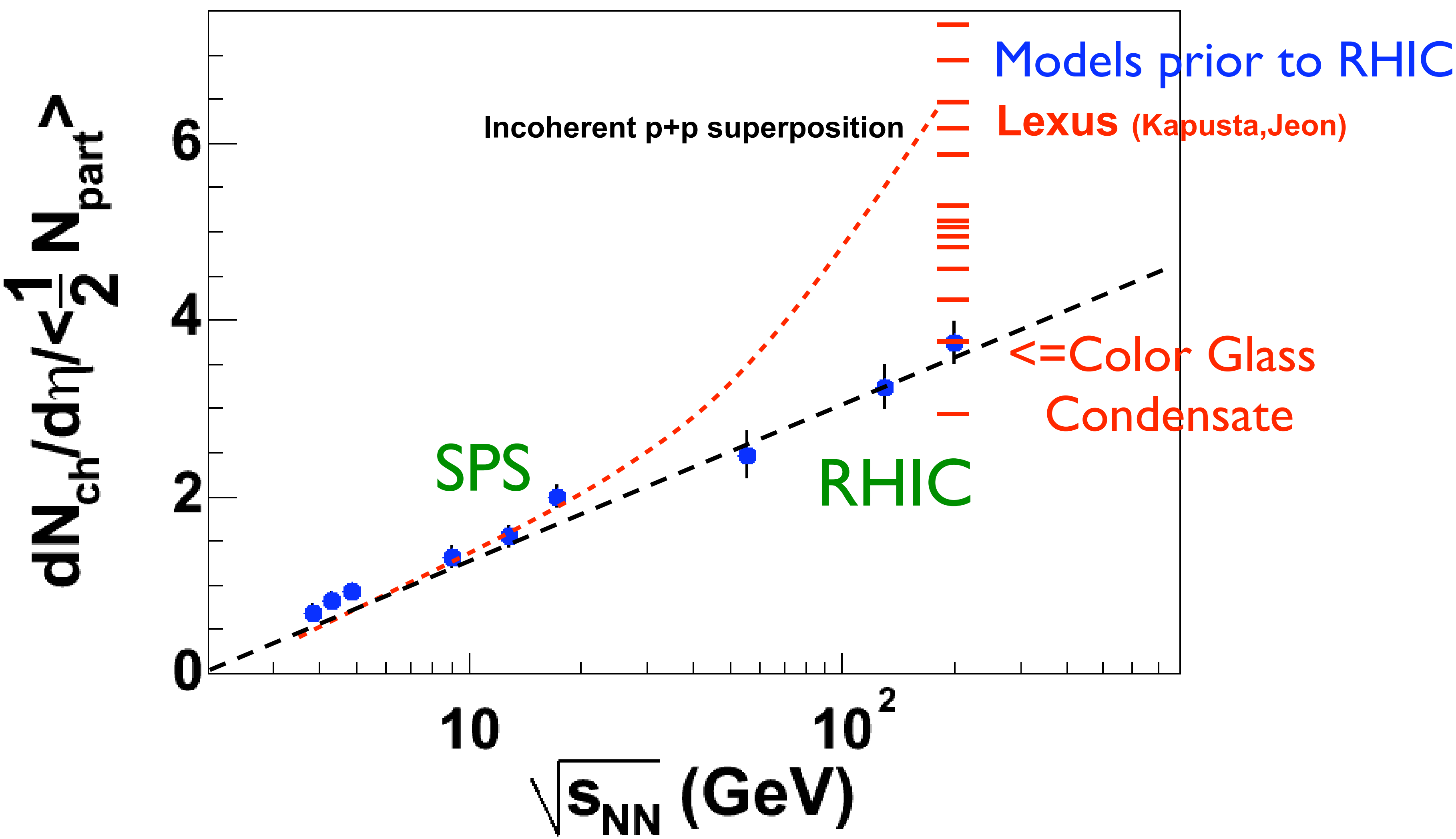
As semi-classical, predicts *logarithmic* growth in multiplicity:

$$\frac{dN}{dy} \sim \frac{1}{g^2(\sqrt{s}/A)} \sim \log(\sqrt{s}/A)$$

First surprise from Day 1: NO big increase in multiplicity. Approx. log growth.

Also: expect avg. momentum to grow similarly $\langle p_t \rangle \sim \log(\sqrt{s}/A)$
(Krasnitz & Venugopalan)

Slow Growth in Multiplicity with Energy



Good fits to overall multiplicity, centrality dependence (Kharzeev, Levin, Nardi)

STAR: from 130 => 200 GeV, multiplicity increases by 14%,
but NO change in $\langle p_t \rangle$ ± 2%. Vs. > 7% increase from Color Glass!

Body of the "Unicorn":

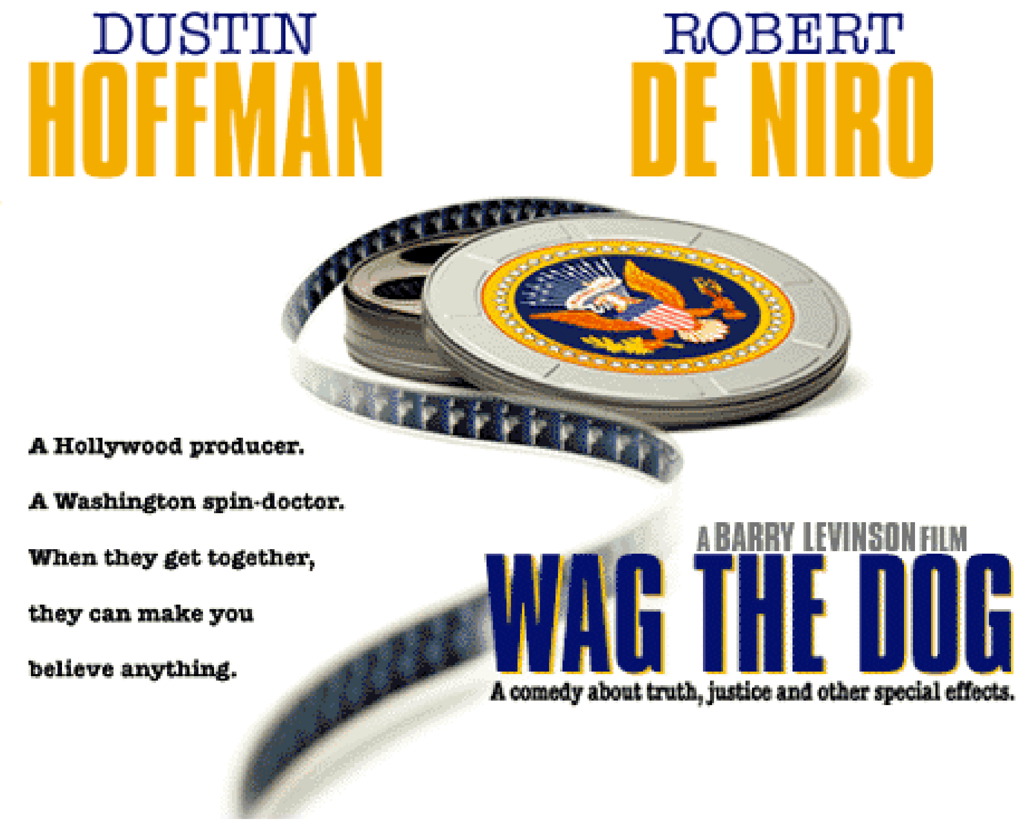
Majority of particles, at small momenta
< 2 GeV.

Tail of the "Unicorn":

Look at particles at *HIGH* momentum,
p_t > 2 GeV, to probe the body.

The Tail wags the (Dog) Unicorn

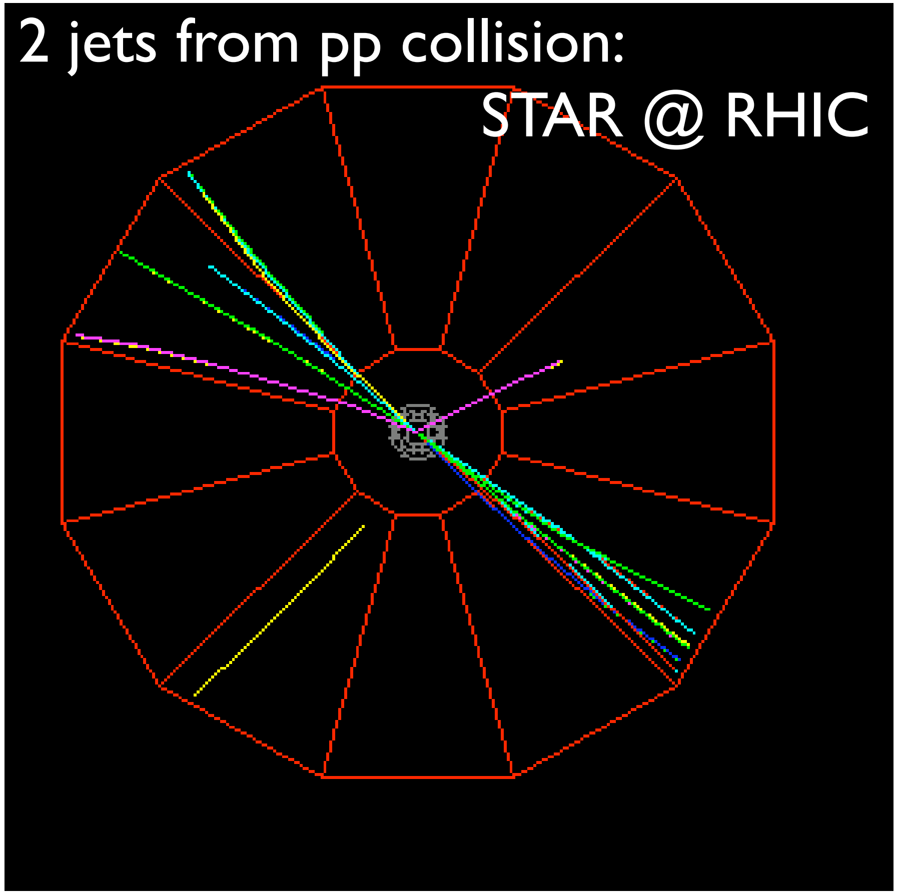
Tail Wags the Dog ≠ "Wag the Dog"



In central AA @ RHIC, there IS "gluon stuff"

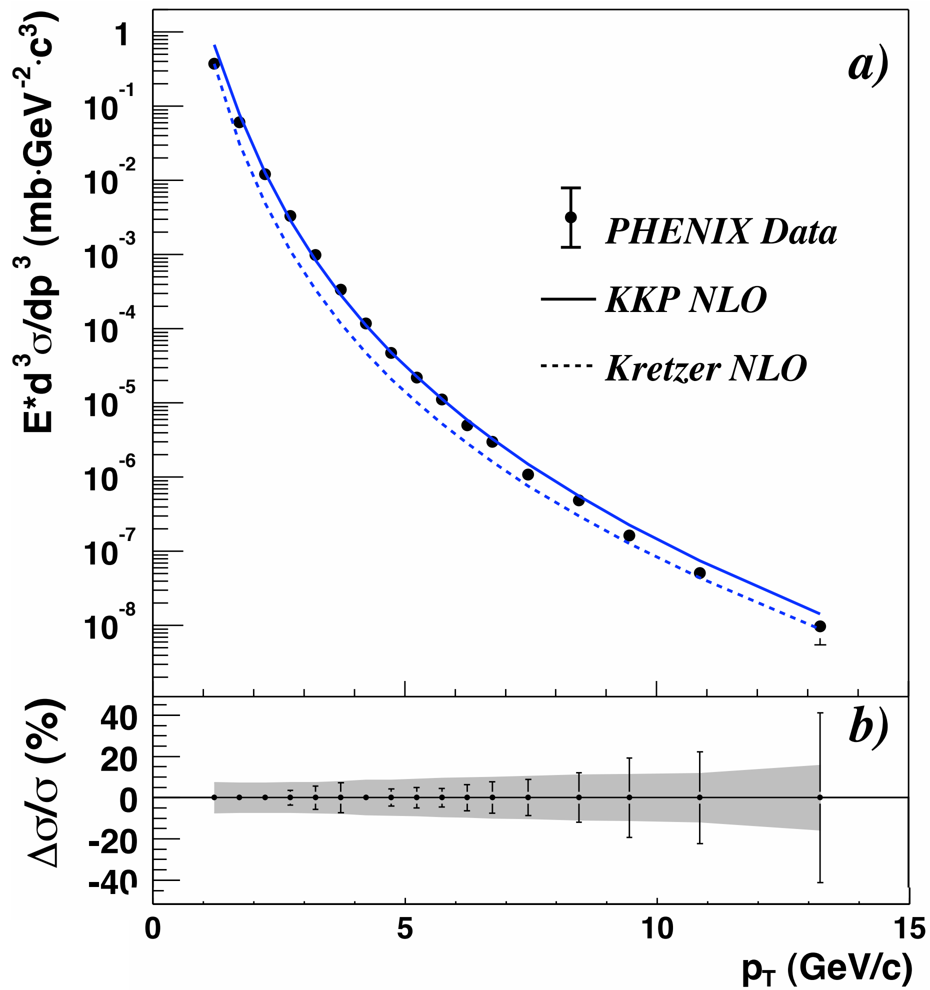
Still no WMD's...

Jets: "seeing" quarks and gluons in QCD



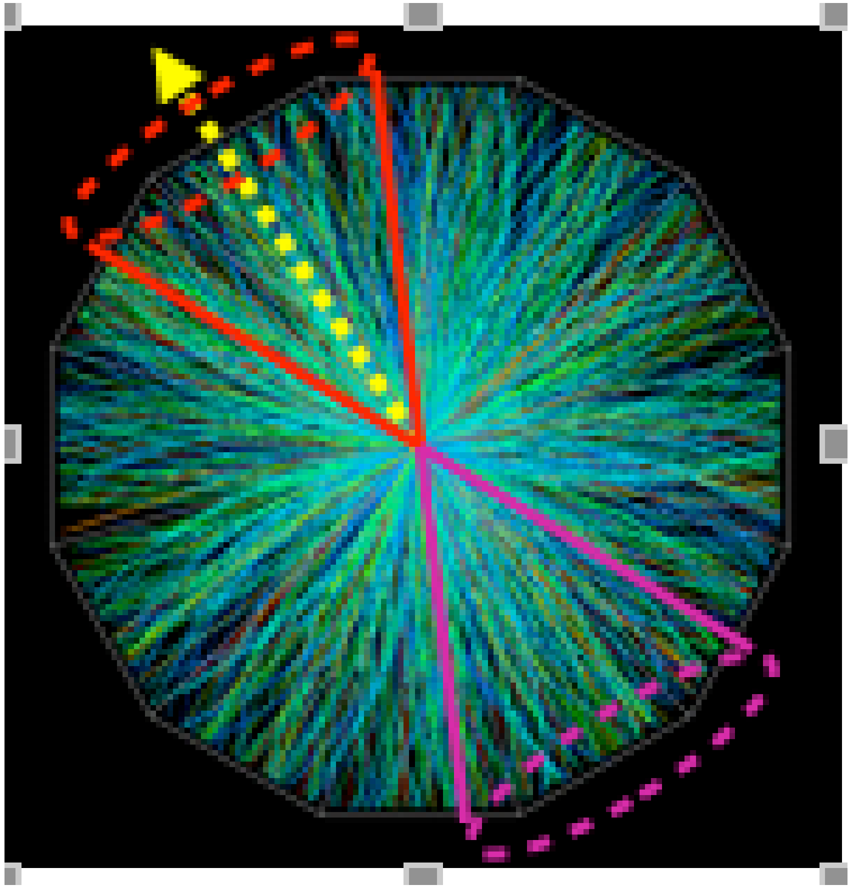
Quarks & gluons => *jets*.
<= jets in pp @ RHIC.
For each jet, there is a backward jet.

Jets can be computed at high energy in pert. thy., down to --- 50 GeV? 5 GeV?
Vogelsang et al =>



“Jets” in central AA collisions

pp collisions: ~ 4 particles/unit rapidity, vs 900 in central AA.
Hence hard to see *individual* jets in AA.



Can construct statistical measures.

p_t = momentum transverse to beam

Trigger on “hard” particle,
p_t: 4 => 6 GeV

Given a jet in one direction,
there *must* be *something* in the
opposite direction.

Look for the “away” side jet, p_t > 2 GeV. (mass proton ~ 1 GeV)

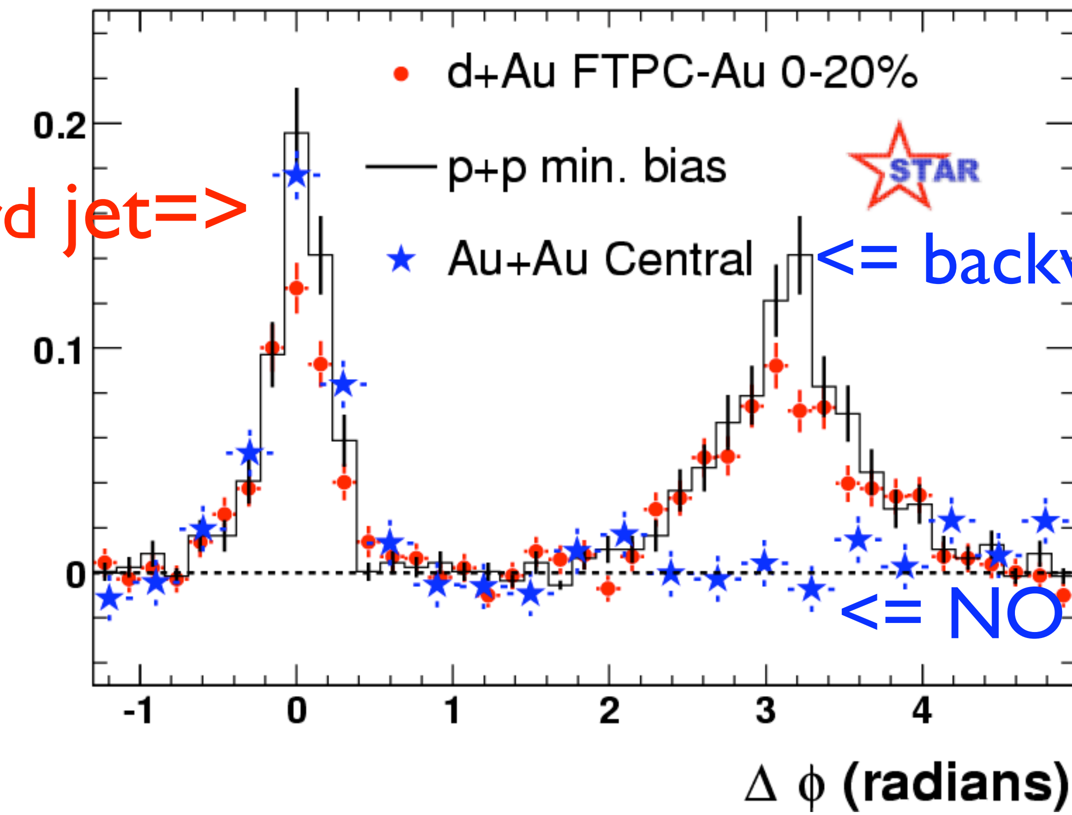
Central AA collisions "eat" jets!

In pp or dAu collisions, *clearly* see away side jet.

In central Au-Au, away side jet *gone: "stuff" in central AA "eats" jets!*

Fast jet tends to lose energy by many soft scatterings off "stuff".

Adams *et al.*, Phys. Rev. Let. 91 (2003)



forward jet=>

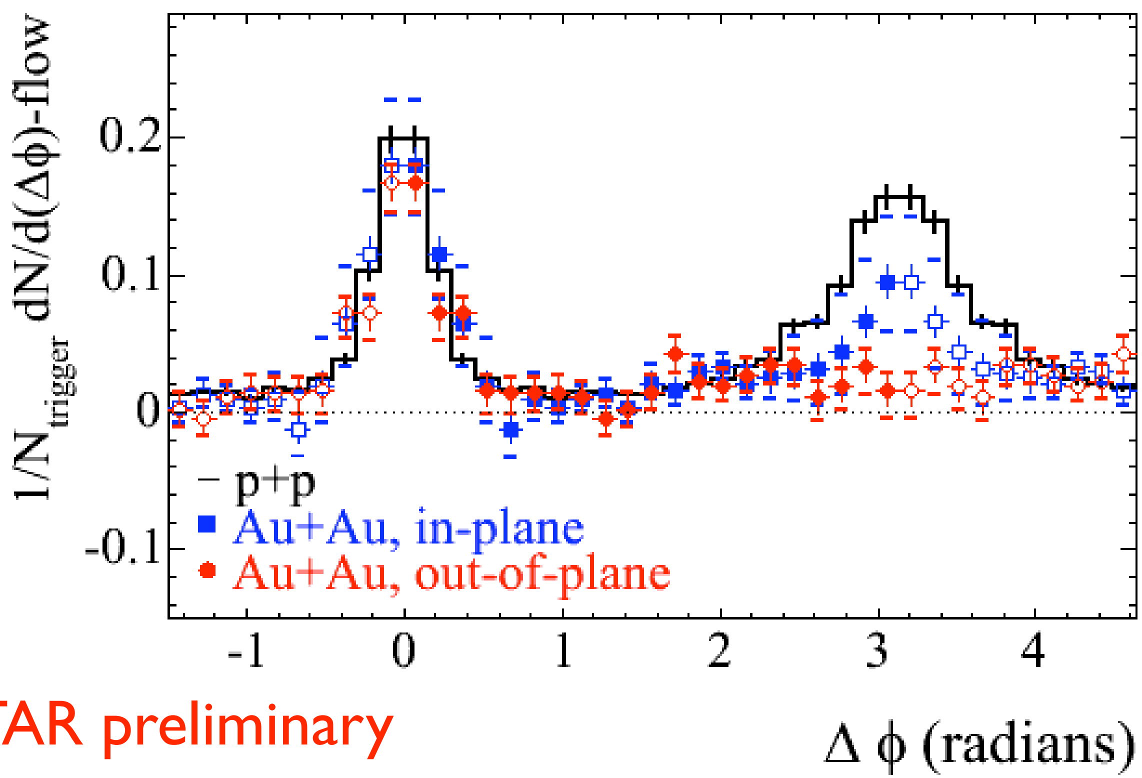
<= backward jet, pp

<= NO backward jet in central AA

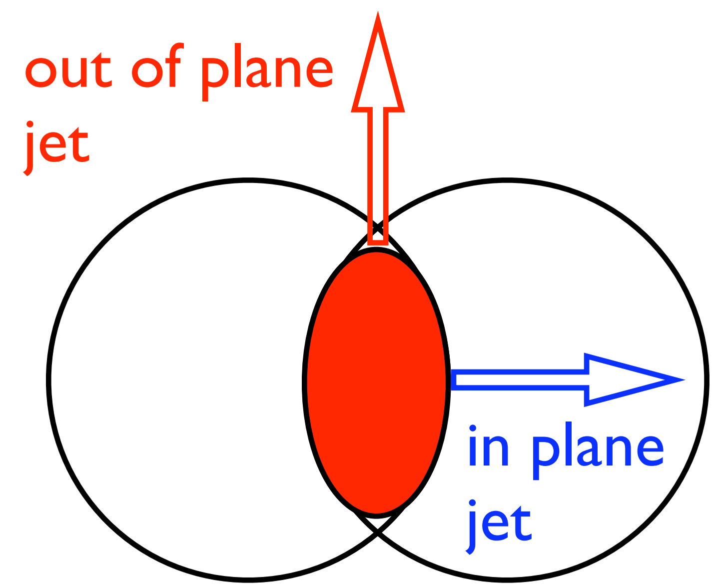
Peripherhal Coll.'s: *Geometrical* Test that AA *Eats* Jets

Peripheral collisions, "stuff" forms "almond": a jet travels farther through the almond, out of the reaction plane, than in the plane.

Exp.'y: backward jet more strongly suppressed *out* of plane than *in* plane => *geometrical* test that central AA *"eats"* jets



STAR preliminary



peripheral collision ↑

almond = "stuff"

Central AA: high p_t jets give low p_t remains!

Trigger on all particles, p_t > .15 GeV.

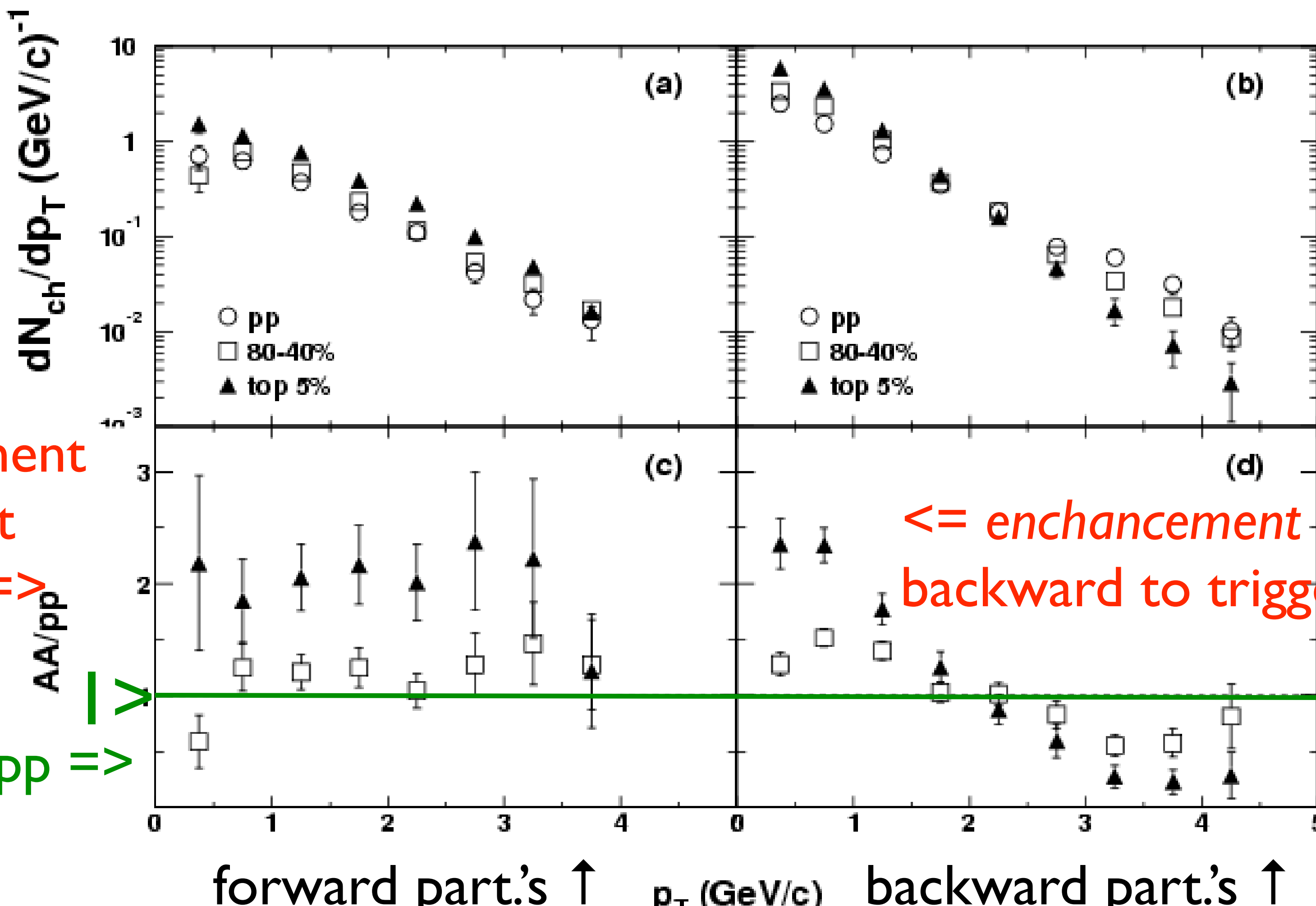
Backward jet: high p_t suppressed, low p_t enhanced.

"Stuff" in central AA slows fast particle down.

Forward jet: enhanced at low momentum: "stuff" dragged along!

raw => spectra

enhancement at low p_t *along* jet =>



STAR prelim.

<= *enchancement* at low p_t backward to trigger jet

1 >

AA=pp

ratio, AA/pp =>

<=*suppression* at high p_t backward

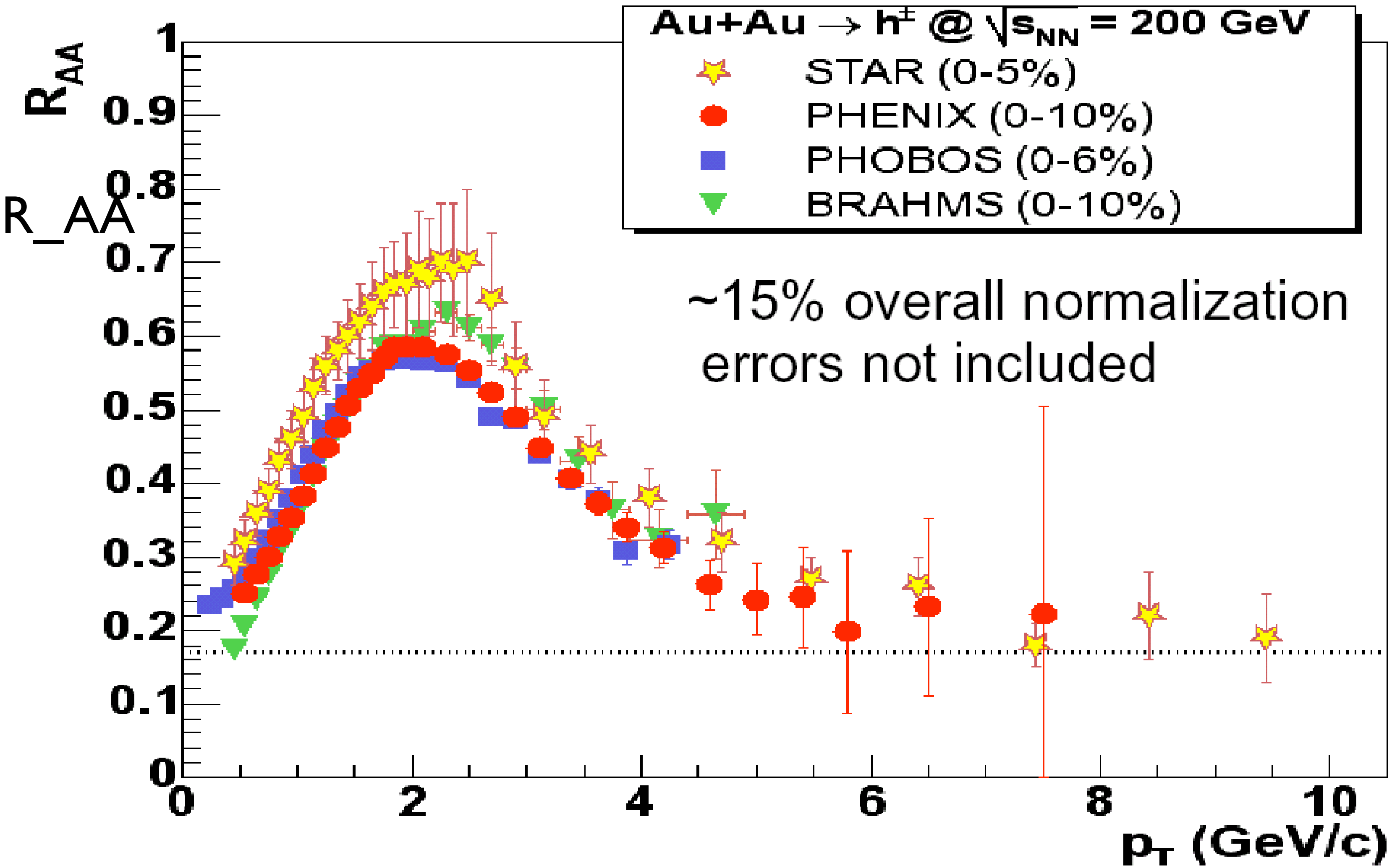
forward part.'s ↑

backward part.'s ↑

Clear Experimental Signal of "Stuff": R_AA

Compare *central* AA spectra to pp spectra, esp. "hard" pt > 2 GeV:

R_AA = # particles at a *given* p_t, in central AA collision/
(# part's at the *same* p_t in pp, *central rapidity* x A^{4/3})



R_AA => *suppression* of hard particles in AA, vs pp.

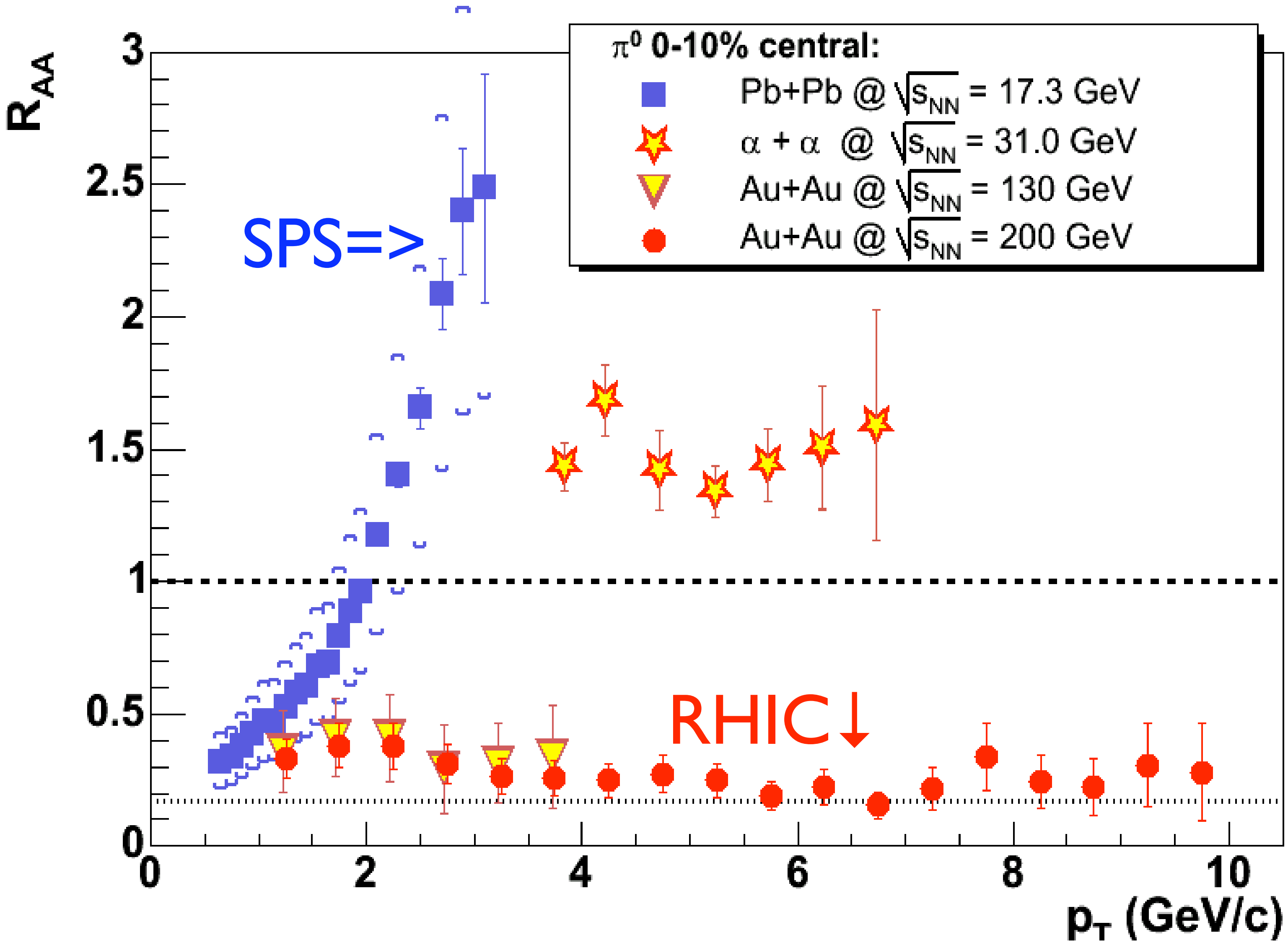
p_t > 6 GeV, ~ *constant* suppression.

R_AA: *Enchancement* @ SPS, *Suppression* @ RHIC

Effect most dramatic for π^0's. SPS: R_AA ~ 2.5 @ 3 GeV. "Cronin"

RHIC: R_AA ~ 0.2 @ 3 GeV.

RHIC: Supp. from *energy loss* - *"stuff"* slows fast particles down.

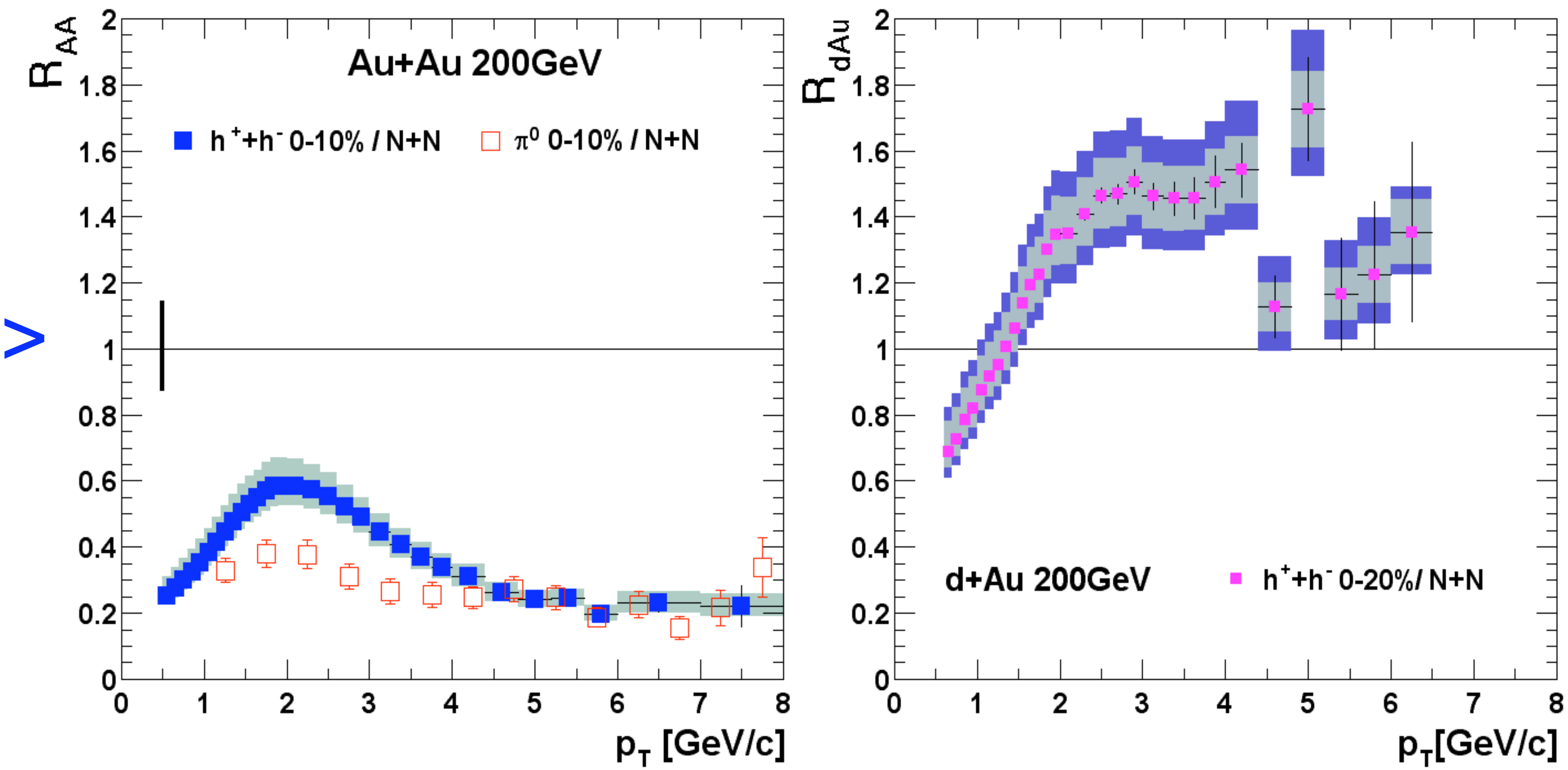


R_AA *final* state effect: *not* seen in R_dA

R_dA: like R_AA, but for dA/pp. *Central rapidity (y=0):*
"Cronin" enhancement in dA, vs suppression in AA.

NO "color glass" suppression. McLerran, Venugopalan, Kharzeev, Iancu...

AA=>

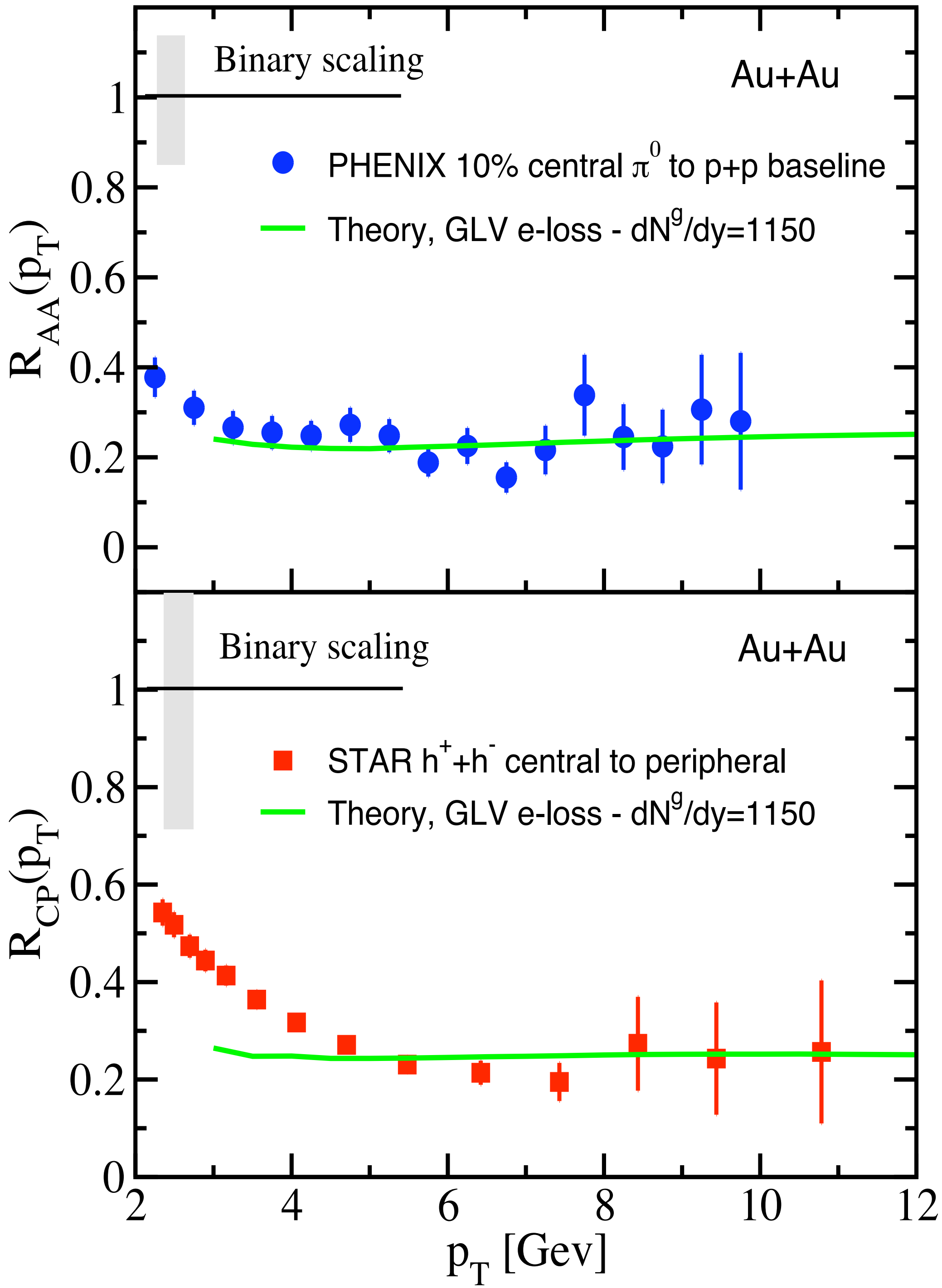


<=dA

Suppression in AA ↑
R_AA ~ 0.4 @ 3 GeV

Enhancement in dA ↑
R_dA ~ 1.4 @ 3 GeV

R_AA: Qualitative Agreement with “Energy Loss”



Energy Loss: A fast particle going through a thermal bath loses energy:
Landau, Pomeranchuk, Migdal ‘50’s
Gyulassy, X.N. Wang, Vitev…Baier, Dokshitzer, Mueller, Schiff, Zakharov

<= Gyulassy & Vitev: *conspiracy* to give *flat* R_AA @ RHIC.

Need to add “Cronin”, shadowing…

Is “flat” R_AA for π^0’s special to RHIC? Will be interesting @ LHC!
When does R_AA => 1?

Where to find the Color Glass: dA, by the *proton*

Fragmentation region: like looking in the rest frame.
Incident projectile gets Lorentz contracted:

proton fragmentation region

nuclear fragmentation region

Nuclear frag. region: proton contracted. Study *final* state effects

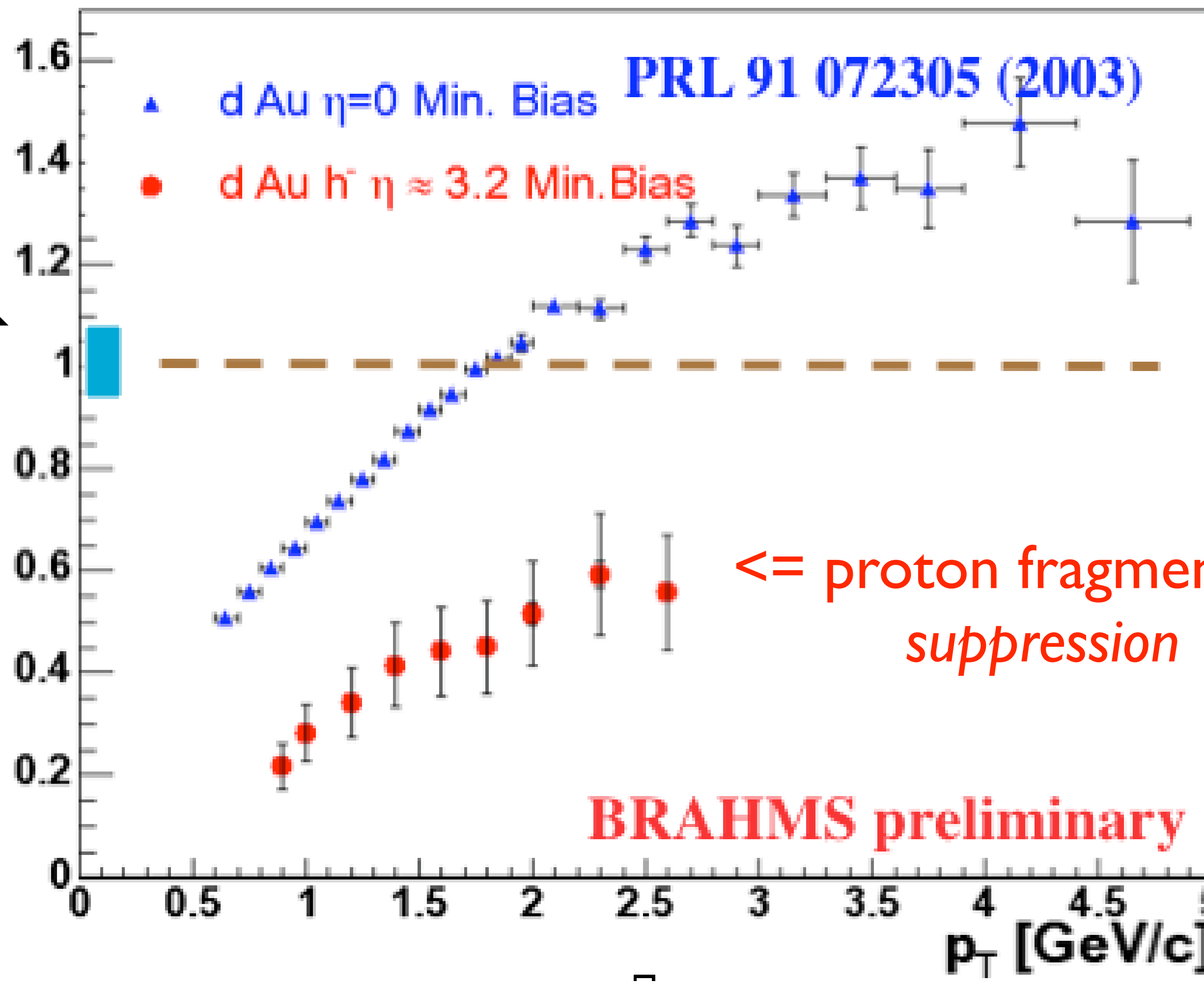
Proton frag. region: study *initial* state effects
(Dumitru & Jalilian-Marian, Gelis...)
Scatter valence quarks off classical (gluon) field=>π+/π- asymmetry

dA, by the proton: *suppresion!*

BRAHMS in dA, *enhancement* @ central rapidity (per. to beam)
suppression @ proton frag. region. (along beam)

Supports color glass initial state.

R_dA↑



<= central rapidity: *enhancement*

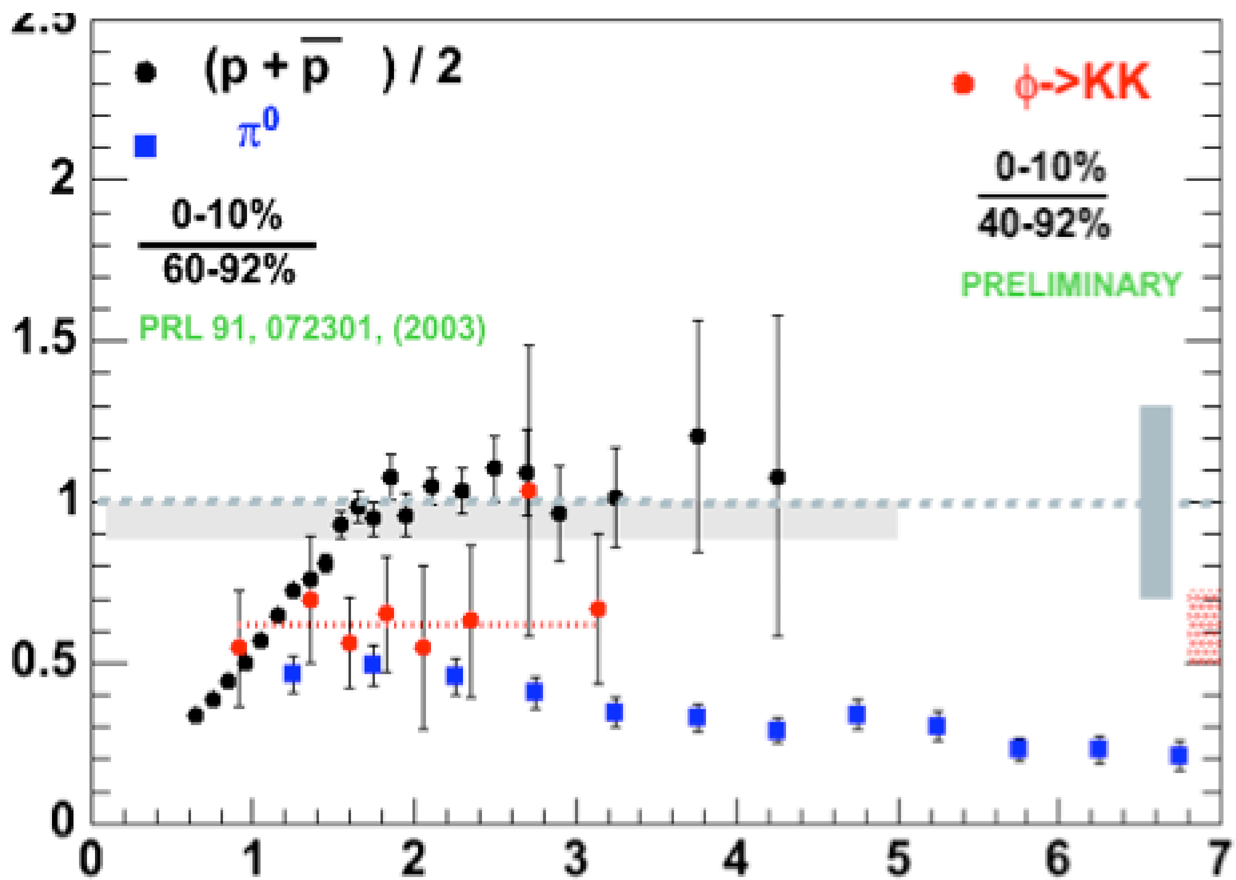
<= proton fragmentation region: *suppression*

Central AA: at p_t 2=>6 GeV , *no* baryon supp.

R_CP: ratio for # particles at given p_t, for central to peripheral collisions
Behaves like R_AA, easier to get data.

Find: *baryons* not suppressed for pt: 2=> 6 GeV, *mesons* are.
Mesons suppressed => "stuff" is *gluonic.*

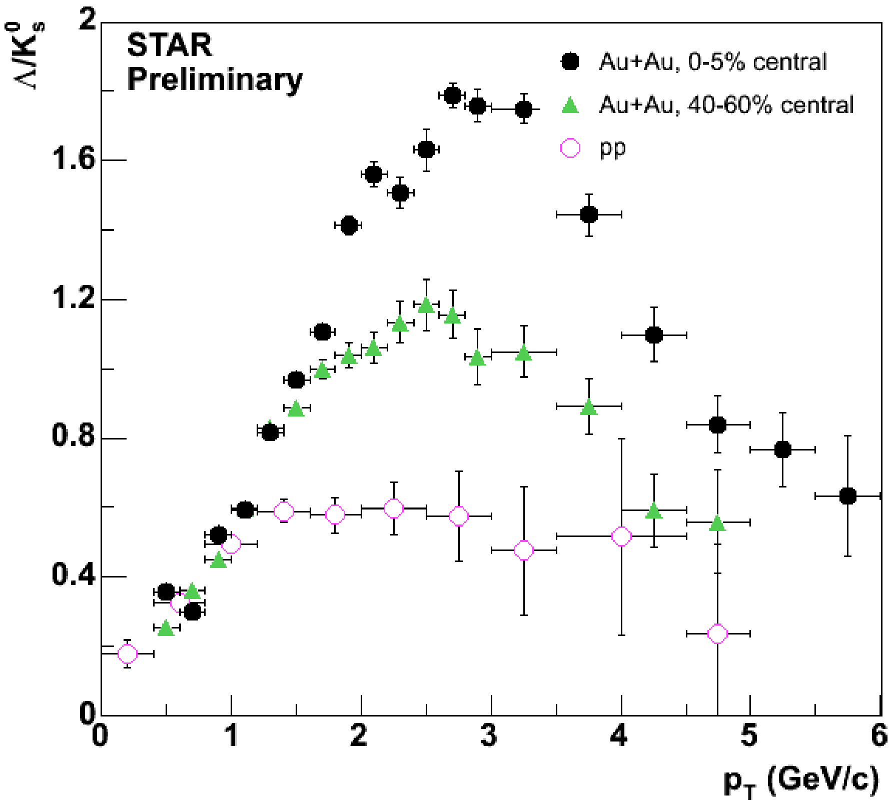
R_CP↑



PHENIX

p_t (GeV)=>

Baryon "*Bump*" at p_t: 2 => 6 GeV



Central AA: *baryon "bump" at p_t: 2 => 6 GeV*

Baryon/meson ratio enhanced by ~3 in central AA vs pp. First seen in p/π.

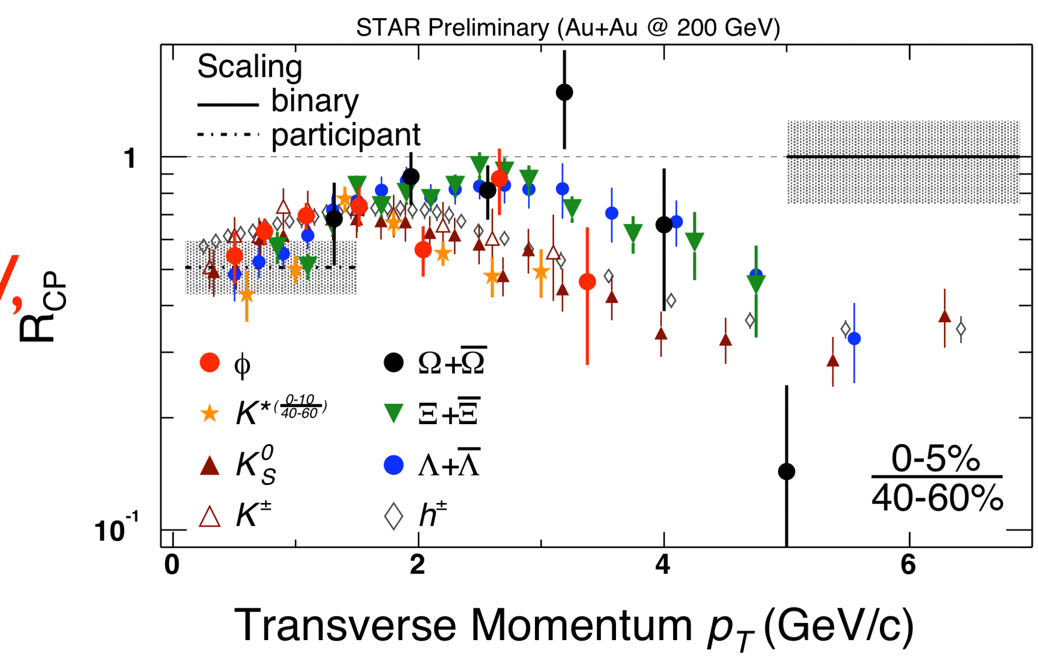
<= Λ/K ratio: bump peaks at ~ 3 GeV.

Above p_t = 6 GeV, ratios like pp.

R_CP vs particle species =>

All particles suppressed > 6 GeV, R_CP ~ 0.2.

=> *Gluon "stuff"* supp.'s mesons, generates baryon "bump"

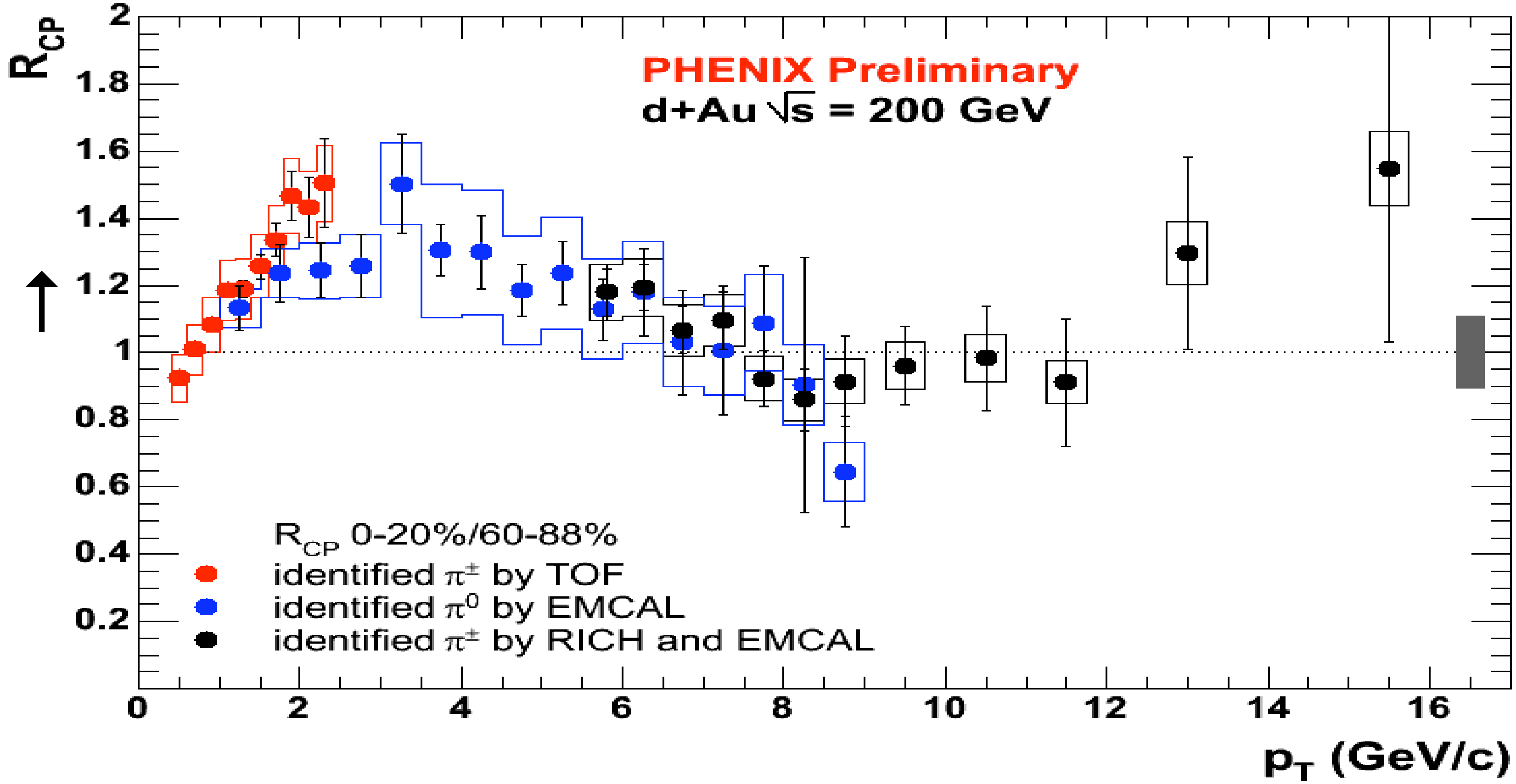


dA: No “Cronin” Enhancement at High p_t

At high p_t, *all* R’s (R_AA & R_CP) should go to one.

In dA, seen in R_CP for p_t ~ 8 GeV.

R_CP ↑

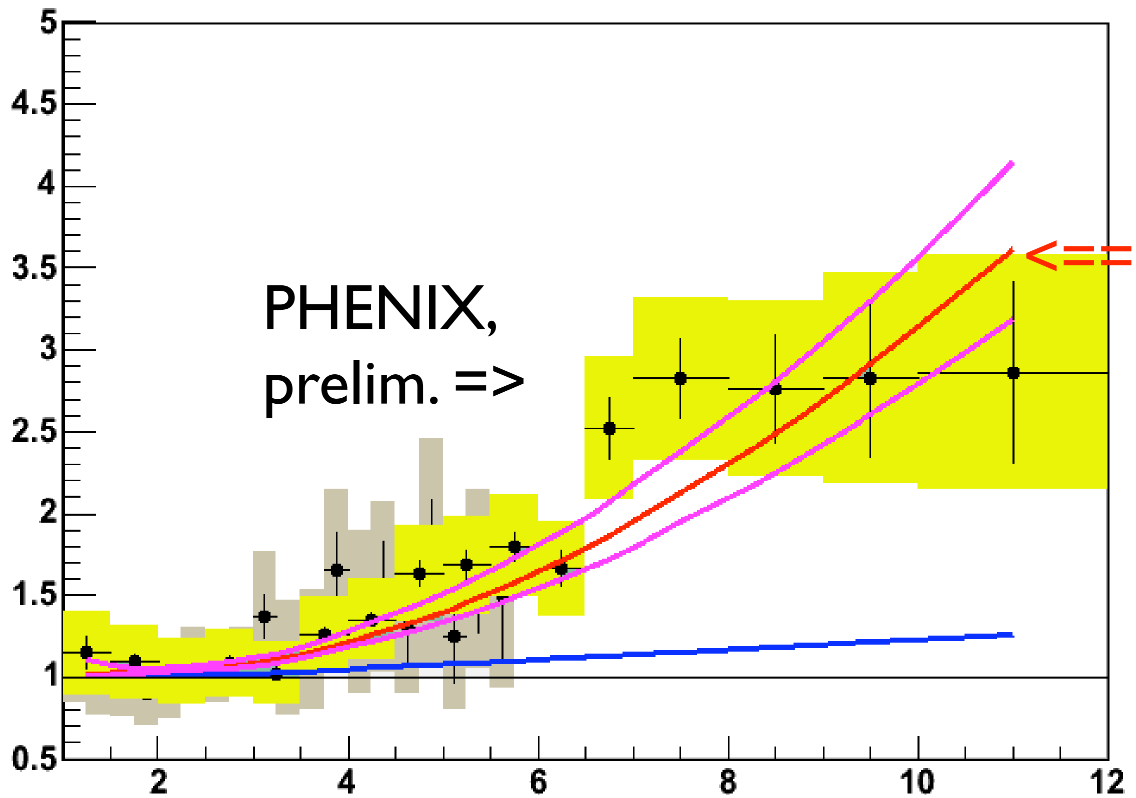


p_t=>

At what p_t does R_AA => 1? > 10 GeV!

Direct Photons Measured

Direct photons: easily escape, so probe initial state. *Without* pion suppression, *very* hard to measure (true at SPS). *With* observed suppression of π^0's, measurable. Reasonable agreement at p_t ~ 10 GeV with Next to Leading Order QCD calculation, = pp times # binary collisions.



The “body” of the unicorn: soft p_t < 2 GeV

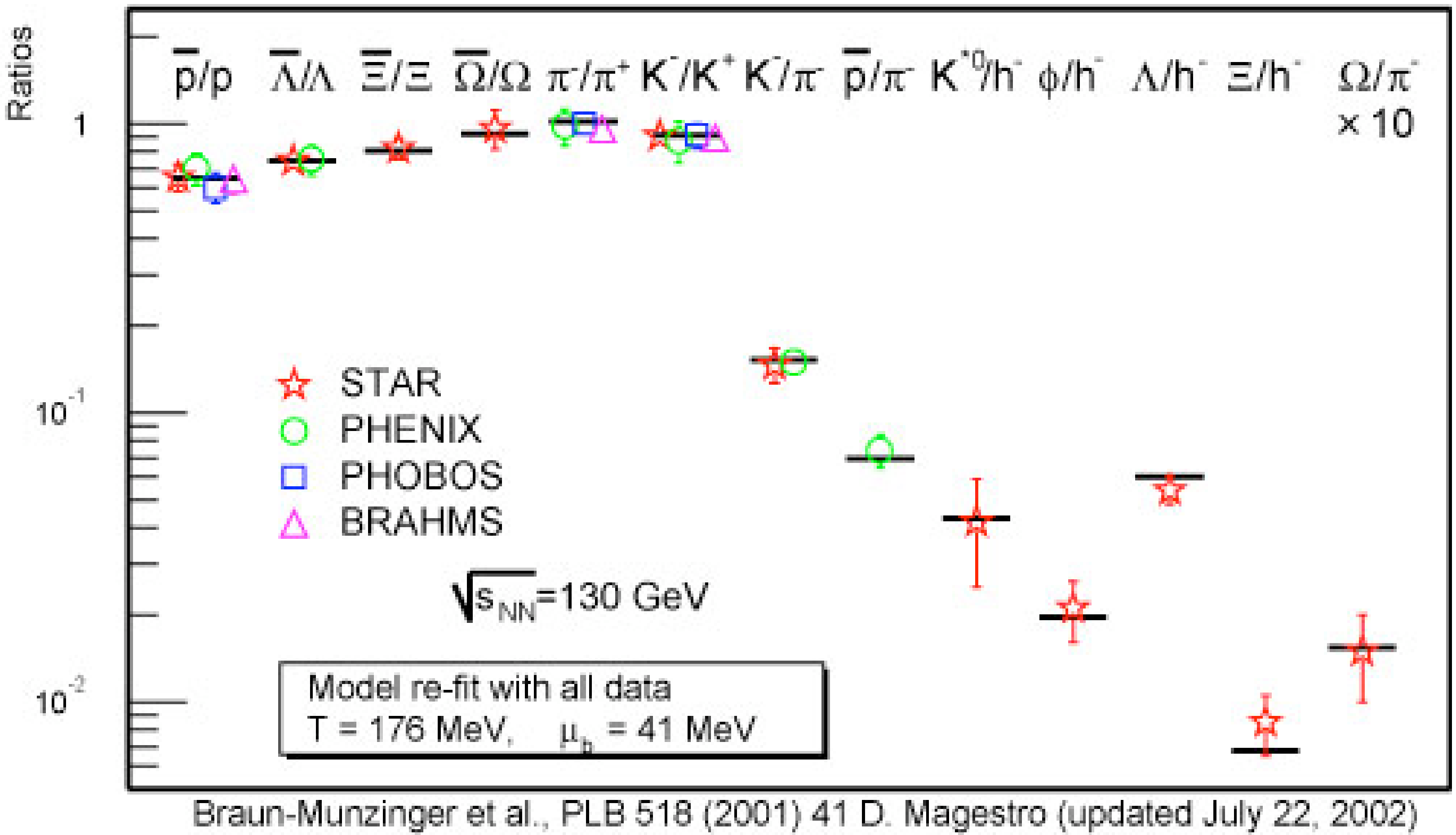
Particles peaked about zero (transverse) momentum
Tc ~ 200 MeV: *expect* thermal to p_t ~ 2 GeV.
Thousands of particles, hydrodynamics should be ok...

“dog”=>

<=unicorn

Total Chemical Ratios *Appear* in Thermal Equilibrium

$$T_{ch} = 175\ MeV$$



OVERALL chemical abundances *well* fit with T_ch = 175 MeV, μ_baryon ~ 0

(Becattini, Braun-Munziger, Letessier, Rafelski, Redlich, Stachel, Tounsi...)

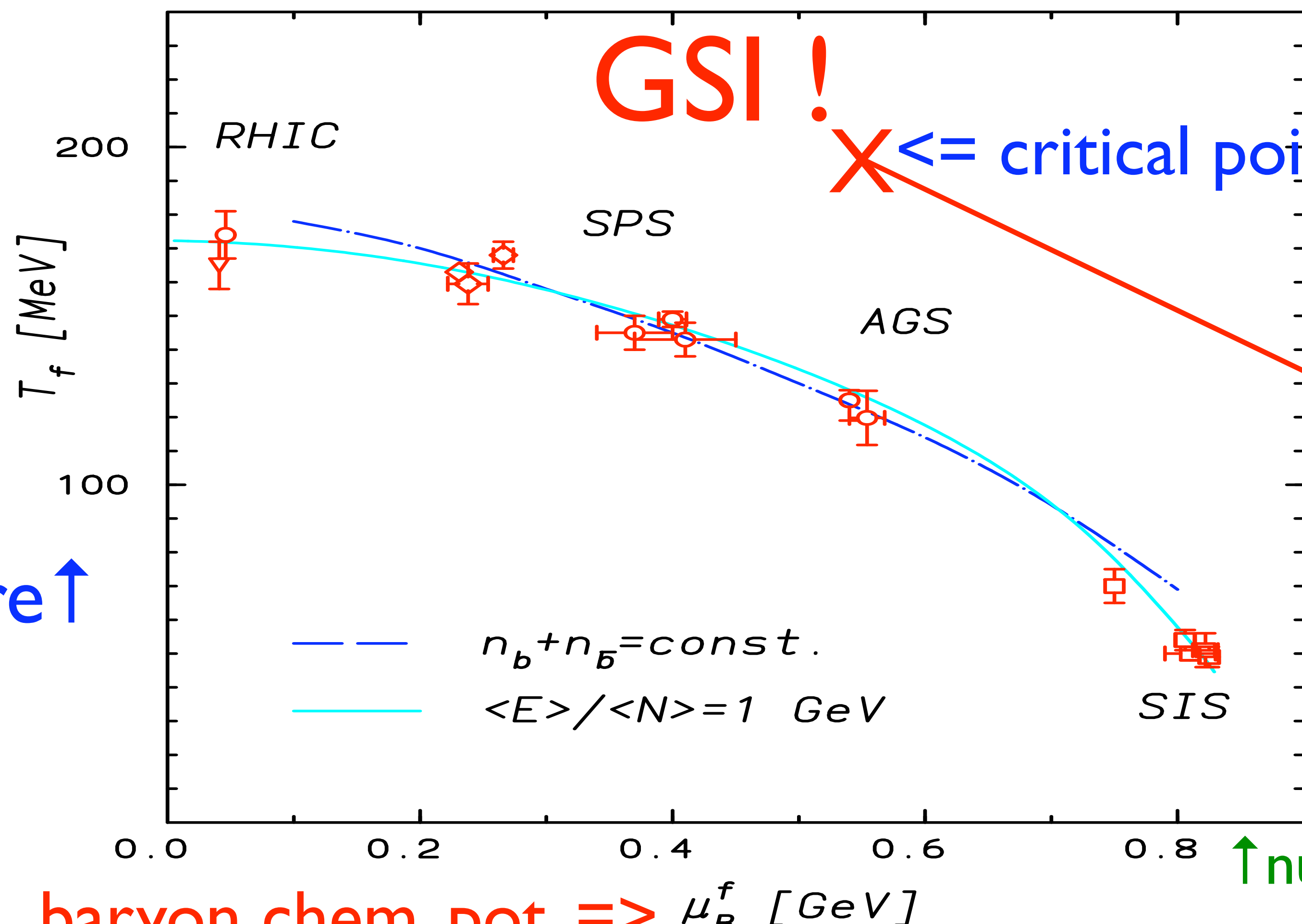
N.B.: even for multi-strange baryons, with relative abundances ~.1% of pions.

Exact critical point in plane of T & μ

Similar fits also work at lower energies. Need baryon chemical potential, μ.

(Apparent) T_ch in pA, pp - *everywhere!* => *NOT* conclusive.

N.B.: in T-μ plane, expect *exact* critical point - GSI?



Temperature↑

μ= baryon chem. pot. =>

↑nuclear matter

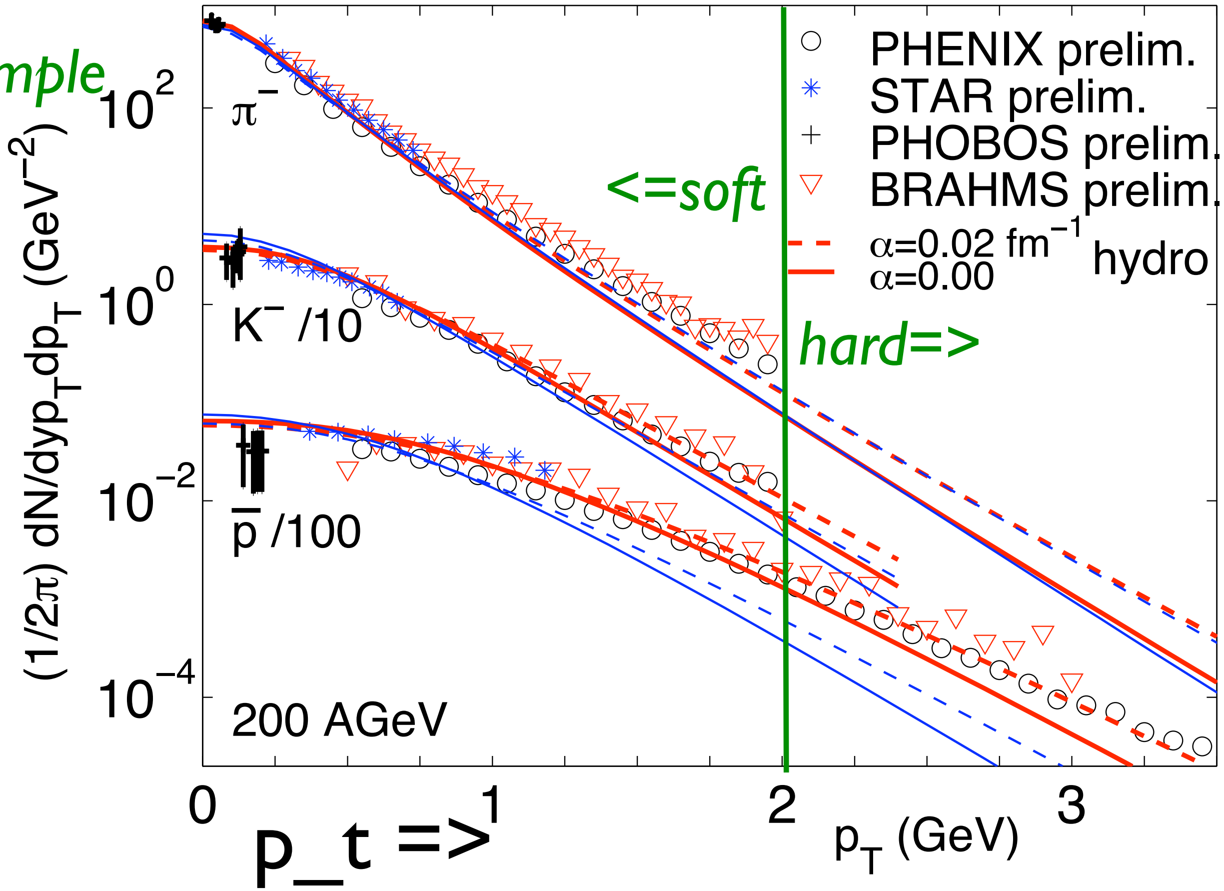
p_t Spectra *Appear* In Thermal Equi. ~ *Hydrodyamics*

$T_{kin} \approx 100 MeV (\ll T_{ch}!)$ *Local* Boost Velocity $\beta \sim .7c$

Hydro. gives good description for most particles, at low p_t< 1GeV.

Assumes initial conditions: starts above Tc in thermal equilibrium, *simple* Equation of State (1st order!)

Ideal hydro.: NO viscosity...



Large local boost velocity β~ .7 c.

Spectra of heavy particles "turn over" at low p_t. β=β(radius).

RHIC: first clear evidence for boost velocity: big!

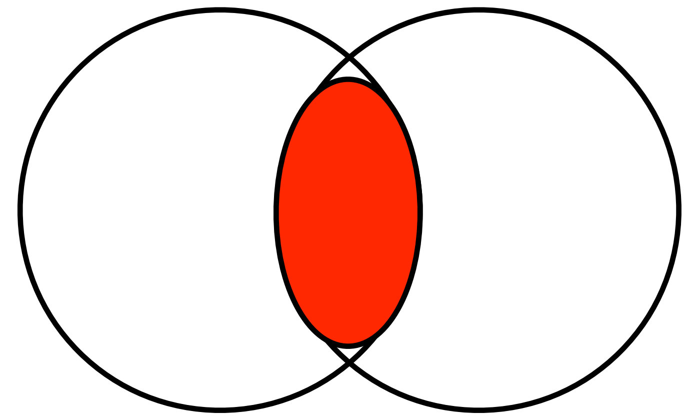
Direct fits similar: "Blast-wave"

Hydro *needs* to assume applicable from *very* early times, .6 fm/c!

Heinz, Hirano, Kolb, Rapp, Shuryak, Teaney... (above Heinz & Kolb)

Success of Hydro.: v2 = Elliptical Flow

Peripheral Coll.'s: Start with system which is anisotropic in momentum space. Exp.'y, compute how *spatial* anistropy => *momentum* anistropy. (Ollitrault, Borghini)



$\uparrow y$

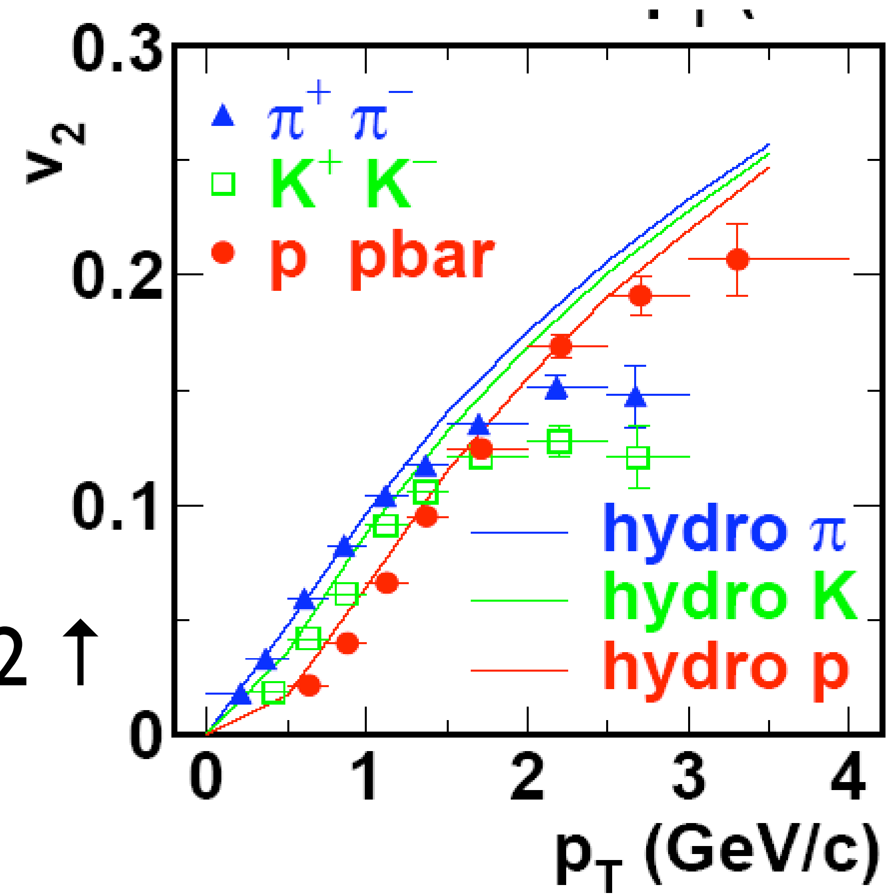
$\rightarrow x$

$$v_2 = \langle cos(2\phi) \rangle \ , \ \tan\phi = p_y/p_x$$

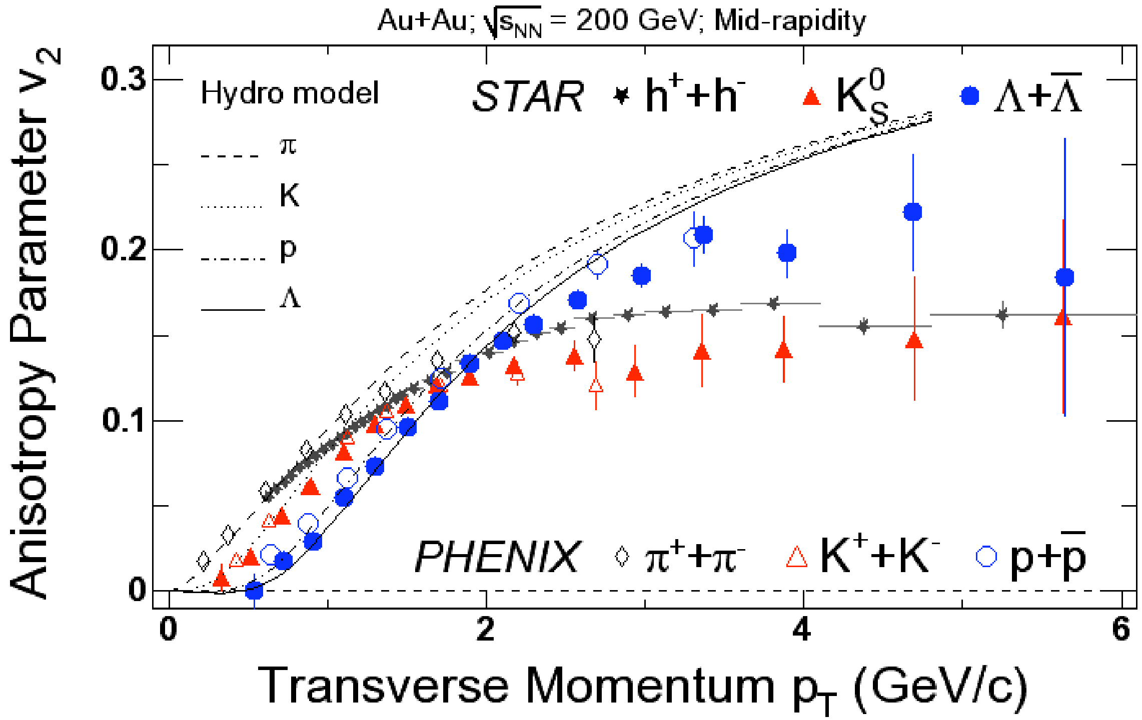
v2 => collective behavior:
there is "stuff", and it sticks.

Hydro works for v2 @ RHIC, not SPS.

v_2 ↑



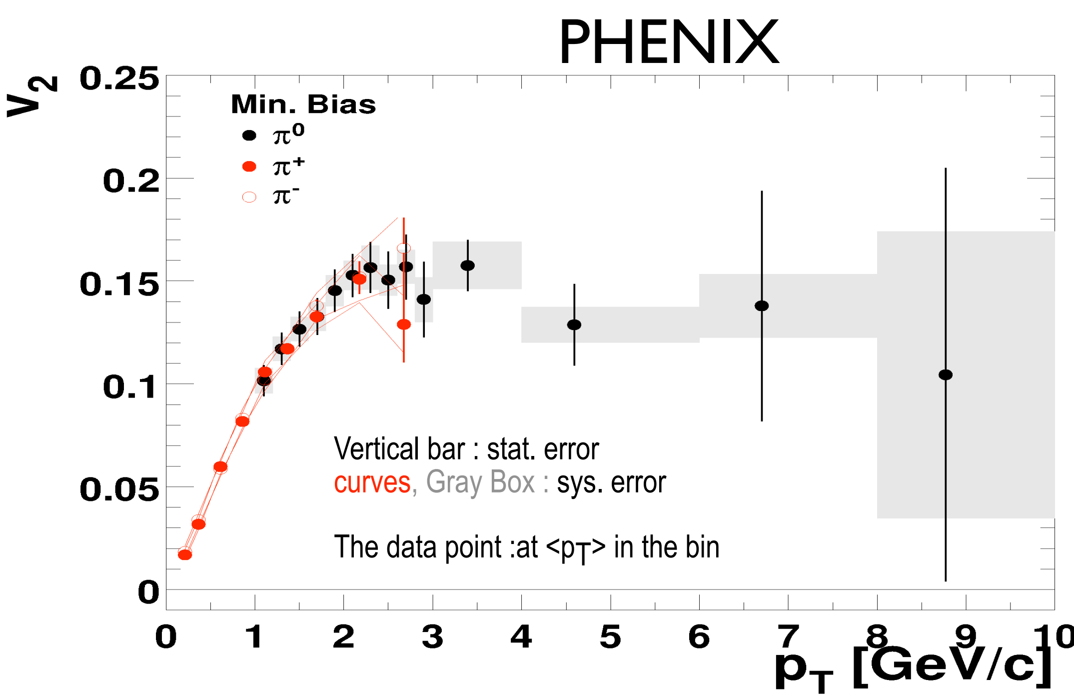
At Low p_t < 1 GeV, Hydro. works for *All* Particles



<= Hydro works for v_2
to p_t ~ 1 GeV for
π's, K's, p's, Λ's…. *everything*.

For *all* particles, v_2 *flat* for
p_t > 1 GeV => 10 GeV - ?!

Is v_2 at p_t>1 GeV measuring
collective flow, or jet-jet correlations?
Apparently: true collective flow.
So why flat?

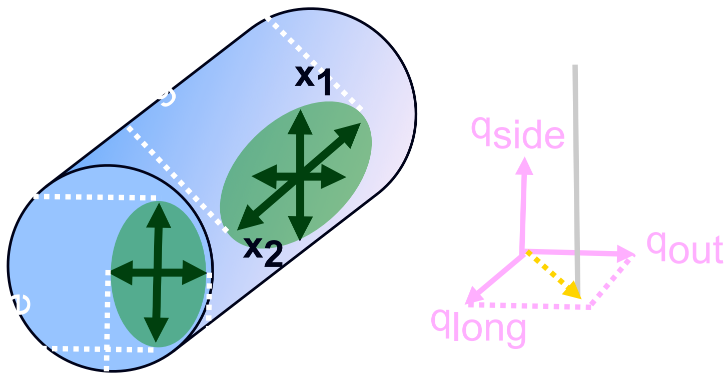


HBT Radii: Hydro *Fails*. *"Blast Wave"* Works

Hanbury-Brown-Twiss: two-particle correlations for identical particles

Sizes at freezeout. *Three* directions, Bertsch & Pratt:

along beam R_long., along line of sight R_out, perpendicular R_side.



$$C(p_1,p_2) = \frac{N(p_1,p_2)}{N(p_1)N(p_2)}$$
$$= 1 + \lambda \exp(-R^2(p_1-p_2)^2)$$

Hydro: R_out/R_side > 1,

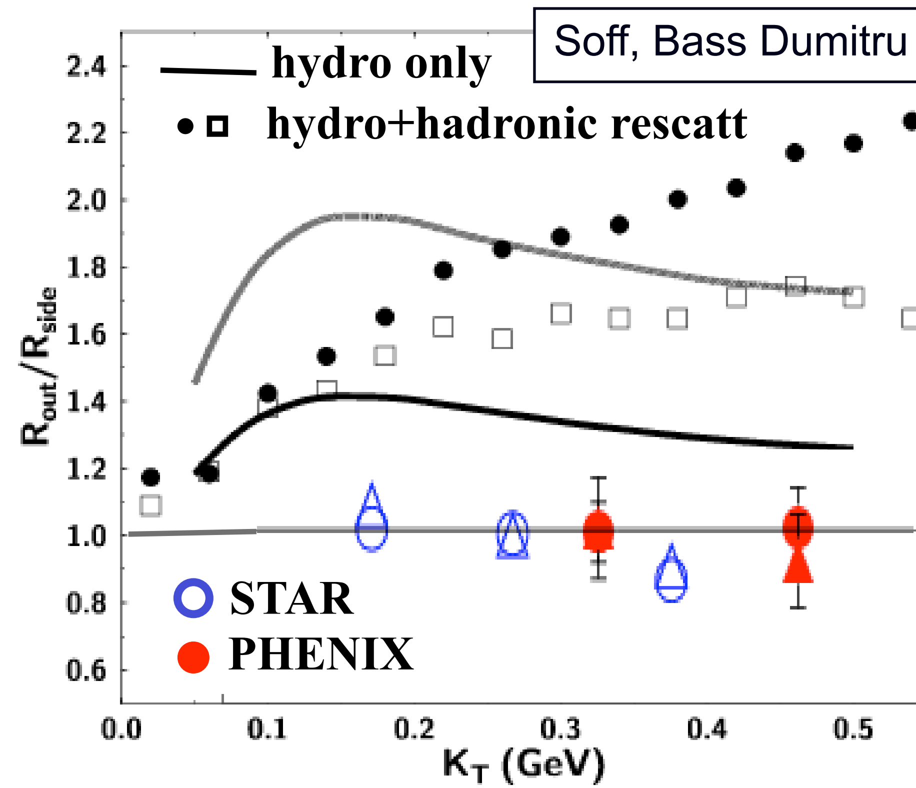
increases with p_t.

Exp.: R_out/R_side ~ 1,

decreases with p_t!

Hydro: R_long, R_out too big.

Peripheral coll.'s: azimuthally Asym. HBT



HBT radii ~ *same* in pp, dA, and AA!

Can also measure HBT in pp, dA...

Ratios behave ~ *same* with p_t!

Can fit HBT radii to "blast wave"
= *fit* not fundamental model.

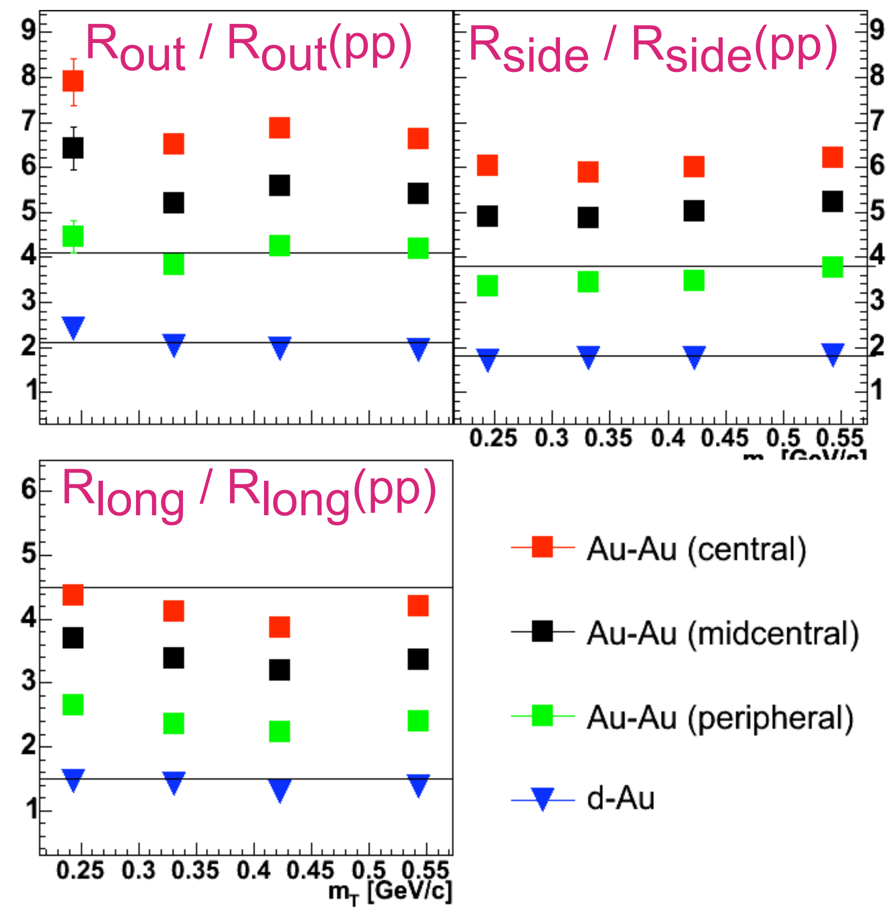
Blast wave suggests:
lifetime ~ 8-9 fm/c, emission ~ 2 fm/c

(No big times from strong 1st order!)

Space-time history "exploding shell"

HBT => *universal* hadronization?

Fluctuations (p_t...) *NOT* same in pp, dA, AA....



m_t ~ p_t=>

STAR prelim.

Has RHIC found (tamed) the "Unicorn" = QGP?

New final state effects:

R_AA

Suppression of backward jets

Also: new initial state effects,
BRAHMS:Color Glass in forward dA

Exp.'y: for the unicorn of central AA,
the high p_t "tail" wags the
low p_t "body"

HBT=>*universal, explosive*
hadronization?

Perhaps: it is a different beast....
But its still a *NEW* beast!

"A possible eureka."